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Linking Estuarine Water Quality and Impacts on Living Resources:

Shrinking Striped Bass Habitat in Chesapeake Bay and Albemarle Sound

ENVIRONMENTAL SCIENCES DIVISION

LINKING ESTUARINE WATER QUALITY AND IMPACTS ON LIVING RESOURCES: SHRINKING STRIPED BASS HABITAT IN CHESAPEAKE BAY AND ALBEMARLE SOUND

Project Title: Prioritization of Pollution Control in Estuaries Through Analysis of Temperature and Dissolved Oxygen Habitat Space for Biota

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ABSTRACT

This project seeks to develop strategies and priorities for arresting habitat deterioration and restoring lost habitats in estuaries through identification of critical zones for maintaining living resources. It uses as an example one representative and important estuarine species, the striped bass (Morone saxatilis). Data on summer water temperatures, dissolved oxygen concentrations, and striped bass distribution in Chesapeake Bay and Albemarle Sound, North Carolina, were evaluated to determine/establish if critical zones existed for maintenance of populations. Criteria for habitat suitability for adults and subadults were those identified in freshwater reservoirs ($<25^{o}C$ and >2 mg/L dissolved oxygen).

In Chesapeake Bay, two key areas were identified: (1) a zone of residual cool water ($<25^{o}C$) in the vicinity of the William Preston Lane, Jr. Memorial Bridge (Bay Bridge) near Annapolis, where striped bass subadults and adults congregate in summer, and (2) a shallow sill near the mouth of the Rappahannock River, where warm surface waters ($>25^{o}C$) in summer impinge on the bottom and may block egress of striped bass subadults and adults from the bay. Increasing anoxia in the bay in recent years, especially in the residual cool water, has reduced the amount of suitable habitat available. Severe deoxygenation in the summer of 1980 and 1984, which would have affected resident adults and newly maturing subadults, is linked to record low values for the Maryland Juvenile Striped Bass Index for 1981 and 1985 in the upper bay. The Bay Bridge and sill areas are suggested as high-priority zones for pollution monitoring and control.

A more limited analysis of Albemarle Sound suggests one key area, a zone of generally deeper water in the western Sound, broadly defined at this time as lying between Pleasant Grove and River Neck, but also possibly including parts of the Roanoke River delta. Progressive deoxygenation of this deeper, western zone since the mid 1970s is suspected from reported algal blooms and other signs of eutrophication. Most aspects of the historical changes in striped bass population structure, including severe reductions in viability of eggs spawned in the Roanoke River since 1974, are consistent with limitation of historically important habitat in summer and resultant physiological stresses and potentially enhanced toxicant exposure that affect reproductive competence.

INTRODUCTION

There is a need to systematically evaluate the impacts of water quality degradation on the biota of estuaries and to develop strategies and priorities for arresting habitat deterioration and restoring lost habitats. Estuaries throughout the United States are experiencing the pressures of increasing human population, including domestic wastes (or the nutrients resulting from wastewater treatment); toxic discharges; power plant cooling water use; and non-point runoff of pesticides, acid deposition, and fertilizers. Notable improvements have been made in the quality of some systems [e.g., the Hudson River, despite continuing PCB contamination (Smith in press)]. Other systems, such as the Chesapeake Bay, are exhibiting alarming trends toward progressive degradation of both water quality and living resources (Officer et al. 1984; Seliger et al. 1985; Boreman and Austin 1985).

Two problems continually plague implementation of good intentions to clean up the nation's estuaries: (1) an unclear relationship between water quality parameters (e.g., temperature, dissolved oxygen, nutrients, chemical toxicants) and the viability of valued populations of the living resources inhabiting the water, and (2) the need to place priorities on cleanup efforts because of limited financial resources. The cost of a general cleanup of a whole estuarine system such as the Chesapeake Bay would be immense, and thus a method for detecting and prioritizing areas of water quality degradation that are most significant for populations of important organisms seems essential.

This project addresses and links these problems. The overall project seeks to develop a method to prioritize pollution control in estuaries through analysis of two water quality parameters--temperature and dissolved oxygen--found to be especially important for one key estuarine species, the striped bass (Morone saxatilis). The Chesapeake Bay, where water quality degradation and decline in populations of striped bass are concurrent concerns, is taken as an initial example for analysis. Preliminary considerations toward generalizing the concepts have been made through study of another estuary in which striped bass populations are threatened, Albemarle Sound, North Carolina.

This report presents a summary of initial results. Analyses and conclusions are tentative and subject to revision. Nonetheless, important conclusions about linkage of water quality and critical zones for striped bass are emerging. These tentative conclusions will be refined further in subsequent work.

A recent synthesis of ecological data on striped bass in both fresh and saltwater environments has concluded that distribution and population declines of this species can be related to habitat selection according to thermal preferences alone or in concert with dissolved oxygen (Coutant 1985). The physiologically optimum temperature range shifts to lower temperatures as striped bass grow. The subadult and adults of the species are limited to zones of a water body that are sufficiently cool and well oxygenated during critical times of the year, such as summer. The size (volume) of the thermally suitable habitat with sufficient oxygen may be a small portion of the water body; thus the annual carrying capacity of the whole system may be restricted.

A number of direct and secondary detrimental effects have been seen in striped bass populations in which adults and subadults are crowded into these "thermal refuges" in summer (Coutant 1985). They include direct mortality of those that can not find the refuge, increased disease due to crowding, deteriorating body condition throughout the summer as food resources are exhausted, overfishing, catch-and-release mortality, and diminished reproductive competence of females the following year (presumably due to a bioenergetic deficit during egg development). Although evidence is not fully conclusive that this type of habitat restriction is important for striped bass declines in estuaries such as the Chesapeake Bay, the evidence is strongly suggestive that it may be a factor.

We emphasize summer habitat because during this season suitable habitat space can be most limiting for many species. Seasonal warming of surface waters, either alone or in combination with density stratification due to salinity differences, can create thermal zones that may match the species' thermal niche in only limited areas or not at all. Microbial respiration diminishes oxygen resources most rapidly in density stratified, warm temperatures of summer. Toxic materials can be most rapidly bioaccumulated and have their most rapid effect in the active summer times of feeding and growth of organisms. Toxicants released into the zones of fish concentration in summer can have effects disproportionate to those they might have if they and the fish were dispersed throughout the water body. Energy stores accumulated in body tissues during the warm seasons are often vital for maturation of gonads in preparation for the next year's spawning. We feel that limitations on summer habitat space can be as critical for population survival as more commonly identified critical areas, such as spawning grounds.

The premise of this work is that identifying habitat limitations for key species in estuaries in summer, due to temperature preferences and seasonal patterns of temperature and dissolved oxygen, will be a productive tool for focusing attention of water quality investigations. This focus should help reduce the cost and effort of estuary study and cleanup to more manageable levels.

METHODS

This work consisted of careful evaluation of existing reports and data sets that may be relevant (no original field study was included). We sought all available historical data on temperatures, dissolved oxygen concentrations, and striped bass distributions in the Chesapeake Bay. We made use of original reports whenever possible. The computerized water quality data base being developed by the U.S. Environmental Protection Agency (EPA) Chesapeake Bay Program is a resource that we attempted to utilize for automated analyses, although coverage of the bay is not uniform in either space or time (Fig. 1). Recent data not yet summarized in reports are not covered adequately. In the case of Albemarle Sound, we conducted a less thorough search of the literature and are indebted to Mr. Anthony W. Mullis, Coastal Research Coordinator for the North Carolina Wildlife Resources Commission, Division of Inland Fisheries, for use of his unpublished data. We consider this report to be interim because we are not confident that our review of available data is yet comprehensive.

We first sought to establish water temperature patterns in the Chesapeake Bay that could direct habitat selection by subadult and adult striped bass based on our results in reservoirs. We assumed that juveniles would occupy shallow, warm zones (Coutant 1985), and they were not included in the purview of this study. The fisheries literature was examined somewhat concurrently for information on striped bass distribution that could be correlated with the thermal regimes. We then sought to describe the spatial and temporal patterns of dissolved oxygen in the bay. We did this from two perspectives: (1) characterizing the changing pattern of summer oxygen resources for the whole bay over the period of record (since about 1950), which includes both high and declining abundances of striped bass (a task that has been attempted by others), and (2) focusing on quantitative changes in dissolved oxygen in specific zones we estimated from temperature analyses to be important habitats for large striped bass. We also attempted to use the computerized water quality data base of the EPA Chesapeake Bay Program to quantitatively graph seasonal and interannual changes in suitable striped bass habitat, as has been done for at least one reservoir (Virginia Power 1986). Following the Chesapeake Bay analysis, the process was repeated in less detail for Albemarle Sound.

A few comments on the success of the process may be fruitful. Despite what seems to have been a large amount of research and monitoring on Chesapeake Bay, the water quality data relevant to striped bass populations are frustratingly spotty. Reasonable hypotheses can be developed based on current understanding, but there are insufficient data in the critical places and times to provide rigorous tests of them (Heinle et al. 1982 also observed this difficulty). A surprisingly large amount of time was required to search the relevant literature and to retrieve reports (many of which were laboratory documents with limited distribution). The laudable computerized data base at the Chesapeake Bay Program offered another slow and sometimes frustrating learning curve to be surmounted before useful information could be retrieved. From both hard copies and computer printouts, we realized that the available data sets are but a sparse and discontinuous sampling of the processes believed to be relevant and important to the dynamic striped bass populations in the bay. Perhaps this study will provide the impetus to monitor selected zones in the future especially well and with unbroken time sequences.

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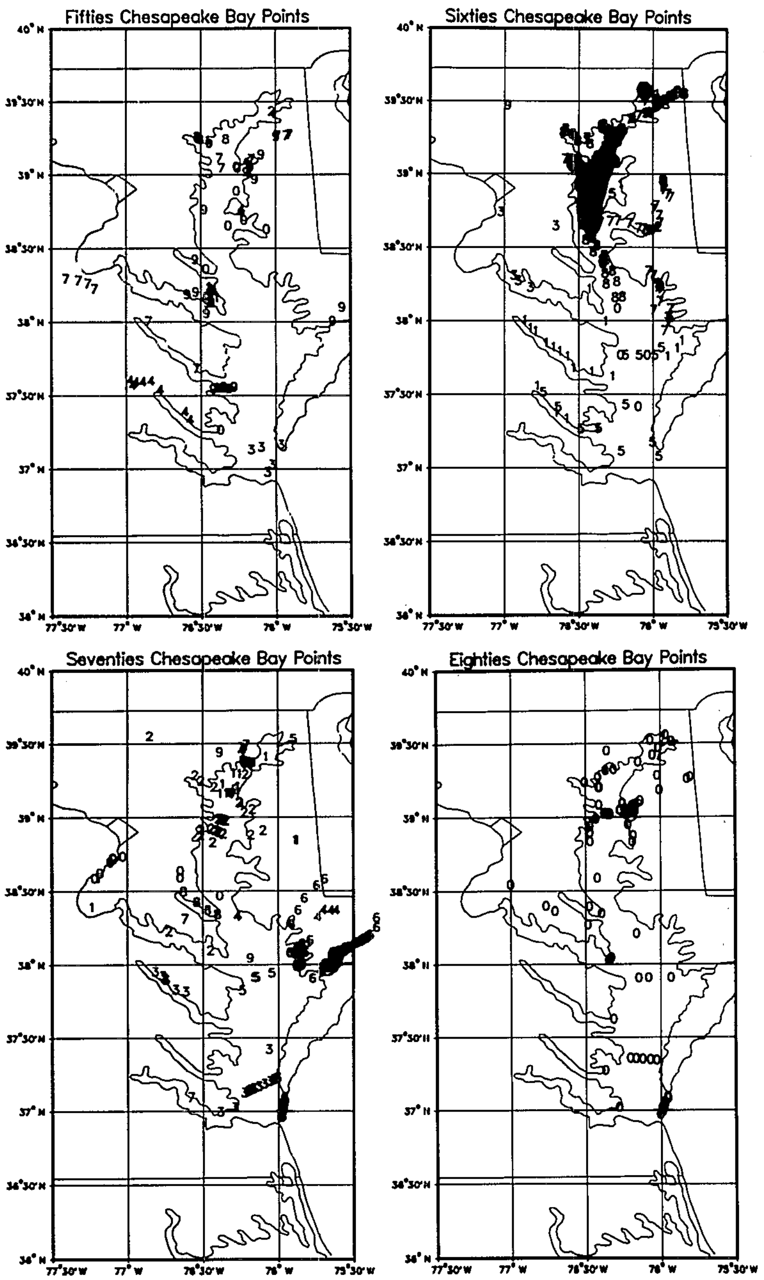

Fig. 1. Sampling locations for July data in the EPA Chesapeake Bay Program computerized data base, by decade from 1950 to 1980. Numbers are the last digit of the year when samples were taken. Locations appearing on land are for tributaries not drawn.

RESULTS

I. Retrospective Confirmation of Striped Bass Upper Avoidance Temperature

Is the upper avoidance temperature of striped bass in an estuary the same as in freshwater reservoirs, where it has been determined precisely with temperature telemetry? Although there have been no detailed studies of temperature selection by this species in any estuary, the existing, independent literature on water temperatures and on seasonal fish distributions can provide a reasonable retrospective test.

The upper avoidance temperature for adult striped bass in freshwater reservoirs in Tennessee has been estimated to be near 25°C (Coutant 1985; Cheek et al. 1985). The temperature range in which subadult striped bass spent 75% of their time in a small Tennessee quarry lake in summer was 20-24°C (Coutant and Carroll 1980). There was clear avoidance of relatively large volumes of otherwise acceptable water in summer when they exceeded these upper temperature ranges. The volumes of water that were avoided included surface layers (Lambert Quarry, Cherokee Reservoir) and main reservoir reaches when cooler tributaries were available (Watts Bar Reservoir). Several other telemetry studies of striped bass in reservoirs have confirmed this general pattern of temperature selection in fresh water, although warmer temperatures up to 29°C have been occupied for short periods when no cool water was available (e.g., Virginia Power 1986). The thermal niche of striped bass has been shown to change with age, with juveniles preferring about 26°C, thus creating habitat partitioning (Coutant 1985, 1986). Earlier research, primarily on juveniles, has misled our view of the habitat requirements of larger striped bass.

We tested the upper avoidance temperature for striped bass of the Chesapeake region by examining the York-Pamunkey River-estuary system. There, striped bass distribution was analyzed in a 1968-69 tagging study by Grant et al. (1970) and in 1967-71 trawl catches by Grant (1974). Monthly water temperature-depth profiles were available along the length of the system and into the main bay for 1956-59 (Massman 1962) (Fig. 2). Additional temperature data were also indicated in Grant (1974), and Brooks (1983a, 1983b) provided extensive data on temperature, dissolved oxygen, and salinity for 1970-80.

The 1956-59 data set is a useful example of the general water temperature conditions (Fig. 3). Water temperatures at the surface and bottom were generally higher in the upper reaches in May-August and fairly isothermal or slightly cooler upriver in September and October. Headwater temperatures were in the 75% occupancy range of 20-24°C in May, whereas lower reaches were cooler. As seasonal warming progressed, the upper reaches warmed above the preferred temperature range and by July, preferred temperatures occurred only in the lower reaches or in the main bay. The August pattern was variable: in a cool year (1957) the entire York system was in the upper part of the preferred range, whereas in a warm year (1959) all temperatures were above those preferred. The entire system cooled to within or below the preferred range in September and October.

Brooks (1983a, 1983b) confirmed that summer temperatures are above 25°C most of the time in the York estuary and that, on the whole, dissolved oxygen is not a problem for fish distribution. Values were almost always above 3-4 mg/L, even in summer. Temperatures seemed to grade smoothly from the York River mouth to the headwaters with no special anomalies.

If striped bass were to follow the preferred temperature range through the seasonally changing temperatures (e.g., crosshatched range in Fig. 3), the fish would move up and down the estuary. Movement would be to the upper reaches in May, and shift downstream in summer while vacating the upper reaches entirely. The striped bass would seek refuge in the deeper parts of the main bay. September or October would see the whole system in the preferred range, thus allowing widespread

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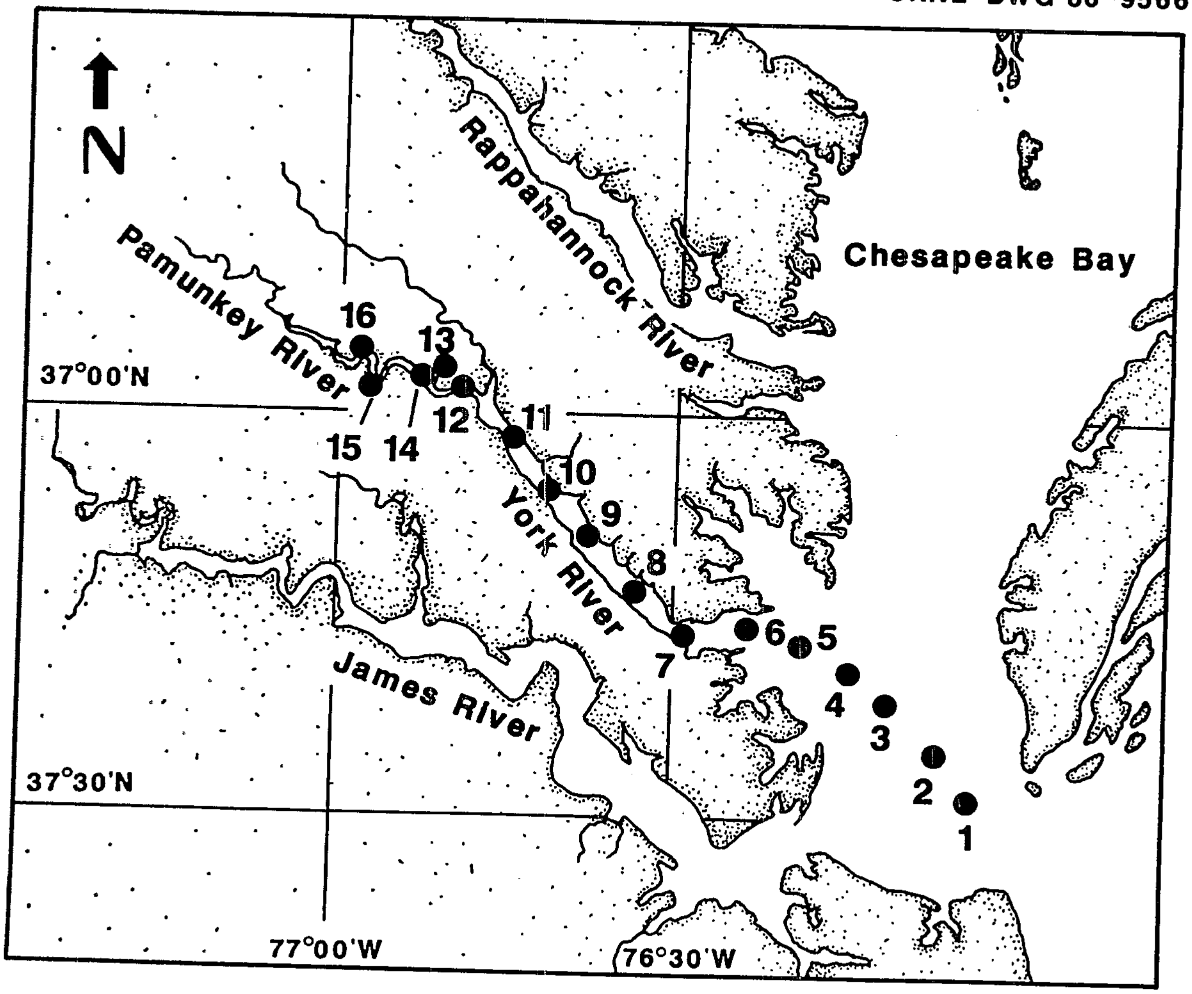

Fig. 2. Stations in the Pamunkey and York rivers and in the Chesapeake Bay monitored for temperature by Massman (1962) in 1956-59.

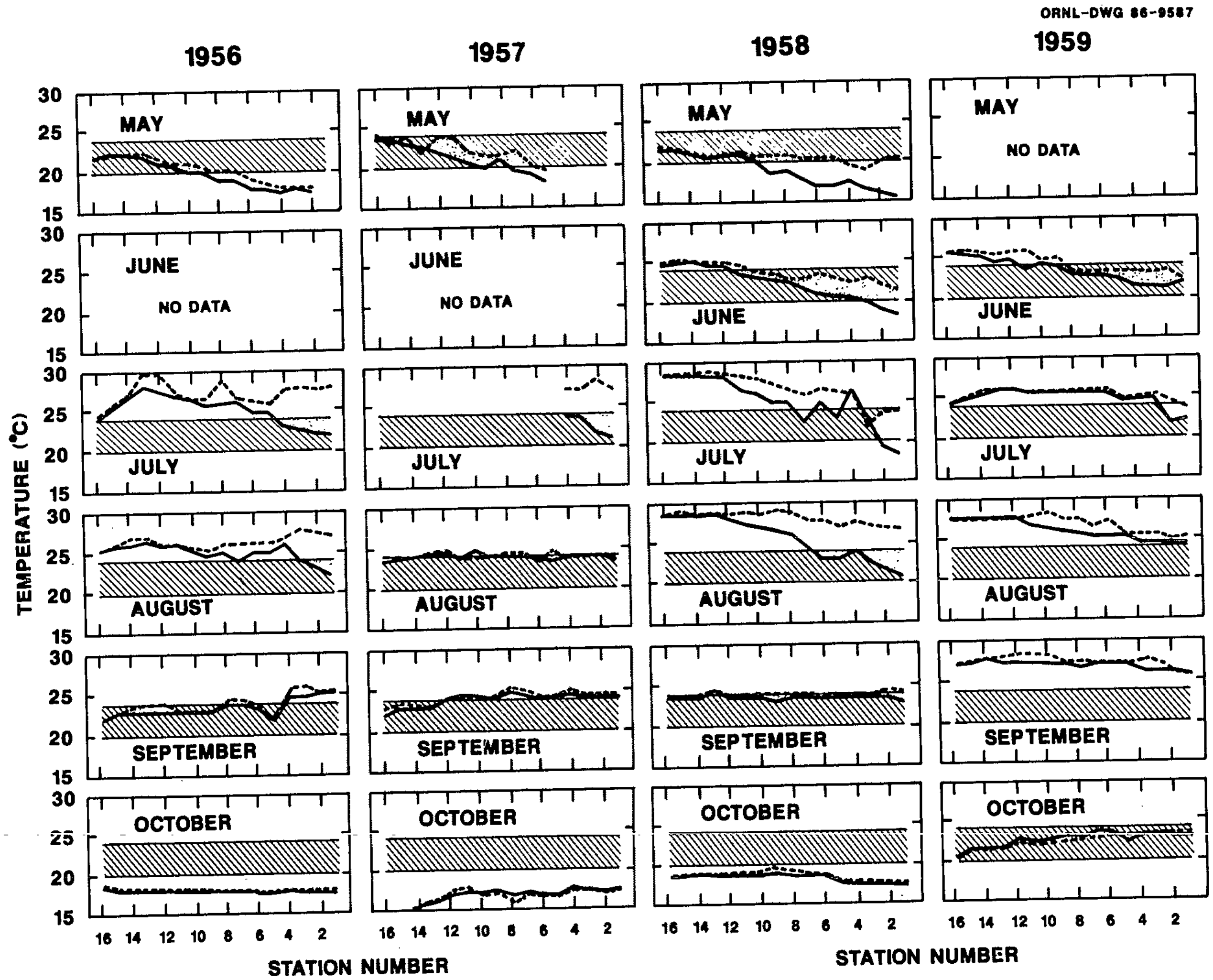

Fig. 3. May-October water temperatures at surface (broken line) and bottom (solid line) in the York River estuary and adjacent Chesapeake Bay sampled by Massman (1962) in relation to the temperatures occupied 75% of the time by subadult striped bass in fresh water (hatched range) (Coutant and Carroll 1980). Station numbers are shown on Fig. 2.

dispersal. Grant et al. (1970) observed that the 2- and 3-year-old striped bass in his tagging study appeared to move from the York River into Chesapeake Bay in warmer months, but return in the fall. Grant (1974) found that mature striped bass caught in the fishery rarely appeared in the river in warmer months. There were anomalously more striped bass in the York River in the summer of 1969; this was a year, however, when there was rapid deoxygenation in the main bay (Taft et al. 1980) and the main bay was warm in summer and had low dissolved oxygen in the deep channel (Price et al. 1985). Habitat restriction in the bay in 1969 may have forced more fish to remain in the York River estuary in summer. Massman (1962) caught few striped bass and provided no fish sizes for catches that correspond directly with his temperature observations.

To the extent possible by matching sketchy fish distribution data in the York estuary to more abundant temperature data, the general range of preferred and avoided temperatures for larger striped bass seems confirmed. Further correlations among existing data sets in the Chesapeake Bay would be desirable, and more confidence would be gained through temperature telemetry studies of Chesapeake Bay fish. Additional confidence in the view that estuarine stocks follow the same temperature cues that we have identified in freshwater striped bass comes from the Connecticut River. There, Kynard and Warner (1987) found that the activity of subadult striped bass at fish lifts was related to temperature and that 72% of fish passage over a 7-year period occurred from 20°C to 24°C. These results seem sufficient to accept the published upper avoidance temperature as the basis for a working hypothesis about habitat suitability for subadult and adult striped bass in the Chesapeake Bay and Albemarle Sound systems.

II. Chesapeake Bay

Summer Bay Residency by Subadult and Adult Striped Bass

Much attention has been paid to the contribution of Chesapeake Bay striped bass to coastal waters where this stock has been dominant (e.g., Kohlenstein 1981) and to seasonal migratory movements. Much less attention has been paid to the seasonal concentrations of fish that remain in the bay. Summer records are particularly scarce because it is not the season of an intense commercial fishery. However, the literature does indicate a historical record of declining residency in the bay as striped bass age and also significant summertime catches of large fish in certain areas, both of which may be correlated retrospectively with water temperature and dissolved oxygen conditions.

From the early tagging and recovery studies of Vladykov and Wallace (1938) onward, it has been recognized that the younger ages of female striped bass (through about age 4) and most of the males tend to remain in the bay throughout the year, whereas the larger females tend to leave. However, departure seems to depend on population density (Goodyear 1978; Kriete et al. 1979). This density dependence suggests a limitation on the amount of suitable habitat for subadults and adults. Goodyear based his conclusion on regressions between New York landings and young-of-the-year densities in the Maryland portion of the Chesapeake 3-6 years earlier. Kriete et al. found that when abundance is average, an insignificant proportion of 2-year-olds (<3%) join the coastal migration; when population is high, more do so.

Substantial numbers (perhaps half) of the females in the year before their first spawning at age 5 remain in the bay (Kohlenstein 1981). This observation could be important for successful spawning in the next year. Mansueti and Hollis (1963) concluded that the principal contribution to natural reproduction is probably from the smaller females between 5 and 15 lb (2.3-6.8 kg) because of their greater relative abundance compared to those larger, even though larger fish produce more eggs per female (Jackson and Tiller 1952).

Some sites of summer residence have been suggested for subadults and adults that could be important spawners in the following year. The information from catch records and personal observations by authors is biased, however, by preponderance of data on smaller sizes and failure of some studies to indicate clearly the sizes of fish. Vladykov and Wallace (1952) indicated "summer feeding grounds" around Tilghman, Galesville, and Rock Hall (105, 115, and 132 nautical miles or 195, 213, and 245 km from the mouth of the Chesapeake Bay, respectively), and that large fish from 6 to 15 lb (2.7-6.8 kg) had been taken by sportsmen during summer months around Rock Hall and Tilghman (Fig. 4). Mansueti and Hollis (1963) cited a June-September 1962 sport fishing survey in the bay bridge area near Annapolis (120 nautical miles or 222 km from the mouth) that reported many large fish as well as smaller ones being caught. About 12% (1300 fish) were >15 lb (6.8 kg). Personal communications from current fisheries biologists in Maryland confirm the importance of this reach of the bay for summertime catches of large fish. Coker and Hollis (1950) noted the disappearance of large striped bass (33.5-106 cm) from mid-bay off the mouth of the Patuxent River (83 nautical miles or 154 km from the mouth) in late June during Navy detonation testing conducted between early May and late August 1948.

Migrations within the bay have been identified in tagging and recapture studies since the 1930s, although most tagged fish have been small subadults. Excepting the high percentages of recaptures near the tagging sites, the most prominent feature has been a movement of fish southward along the western shore in autumn. This movement has also been recognized in the seasonal sequence of catches in pound nets. Dates of tag returns outside the Chesapeake indicated to Vladykov and Wallace (1952) that outward migration from the bay is partly a continuation of the down-bay migration in the fall.

These sketchy observations implicate a particular zone of the bay as especially important for the larger striped bass in summer. It stretches from Tilghman Island at the north of the mouth of the Choptank River about 35 km south of the bay bridge (latitude 38° 40'; 105 nautical miles or 195 km from the mouth) to Rock Hall opposite the southern bank of the Patapsco River (Baltimore Harbor) (latitude 39° 37'; 132 nautical miles or 245 km from the mouth), which is about 20 km north of the bridge.

Temperatures in Chesapeake Bay

Do temperature patterns exist in the Chesapeake Bay that would concentrate the larger resident striped bass in the upper middle bay in summer if the fish selected preferred temperatures? Although the influence of temperature is altered by other factors (e.g., dissolved oxygen, which will be discussed in a later section, and food supply), it is useful to address the simpler question first.

A number of water temperature surveys have been published that are useful for addressing this question. They include the tributary surveys, such as those for the York-Pamunkey system detailed above, and surveys of the main channel of the bay. Records are spotty but include useful information from about 1950 to the present.

Tributary summer temperatures generally followed the pattern described for the York-Pamunkey system (Massman 1962). Without recourse to consideration of other factors, it is quite likely that subadult and adult striped bass find tributary waters unsuitably warm (>25°C) in summer and vacate them. This generalization comes from examination of temperature-depth profiles through the summer season in the EPA Chesapeake Bay Program computerized data base and in original reports (Brooks and Fang 1983 for James River; Brooks 1983c for the Mattaponi River).

Data for vertical profiles along the longitudinal axis of the main bay were profoundly revealing of temperature patterns that would guide larger striped bass. Seitz (1971) provided what appears in retrospect to be a reasonably typical pattern for seasonal changes in warm-season temperatures. He also gave salinities that, along with temperature, strongly influence seasonal water column stratification (Fig. 5).

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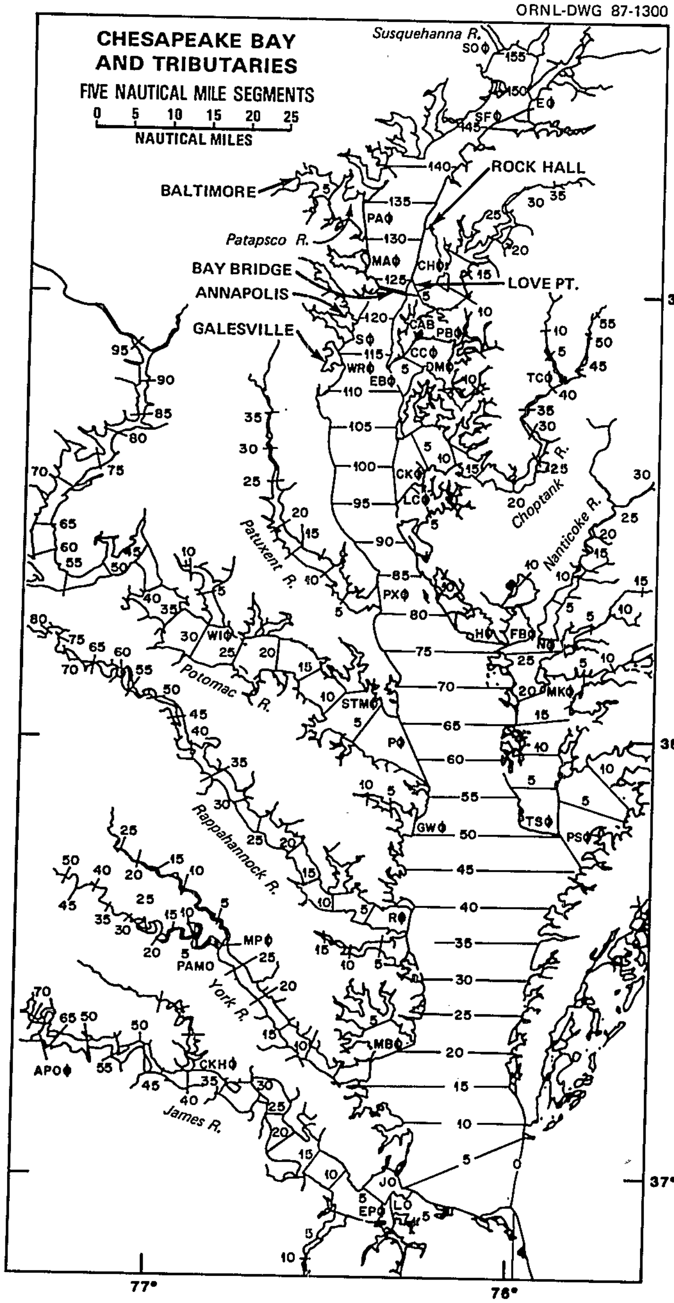

Fig. 4. Chesapeake Bay and its tributaries divided into 5 nautical mile segments and showing features prominent for evaluating striped bass habitat (after Cronin 1971).

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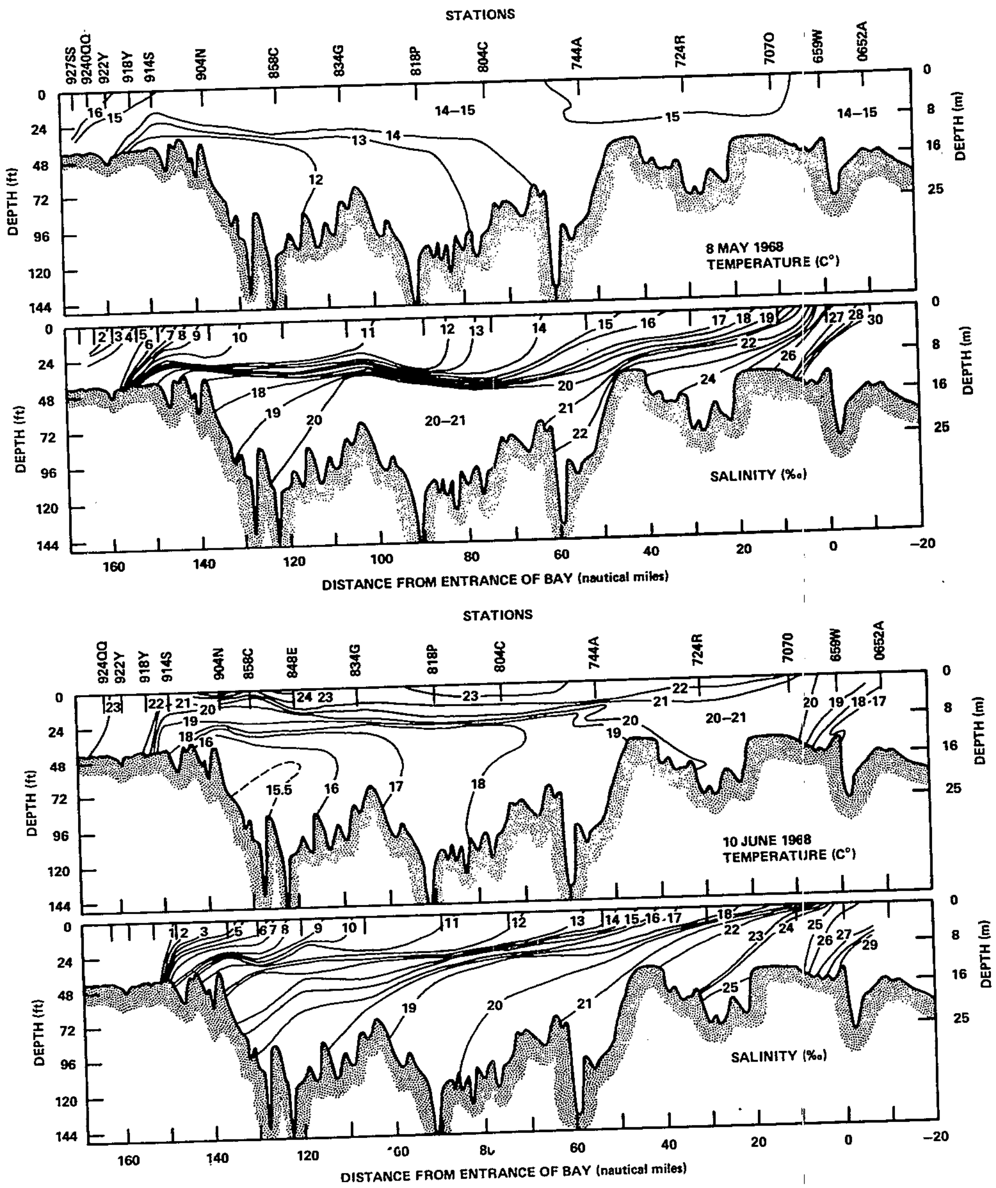

Fig. 5. Temperature and salinity along the longitudinal axis of the Chesapeake Bay for May-October 1968, showing typical density stratification, a summer pocket of cool water centered near nautical miles 120-130, and a summer temperature maximum filling the water column at a shallow sill near nautical mile 45 with temperatures >25°C (after Seitz 1971).

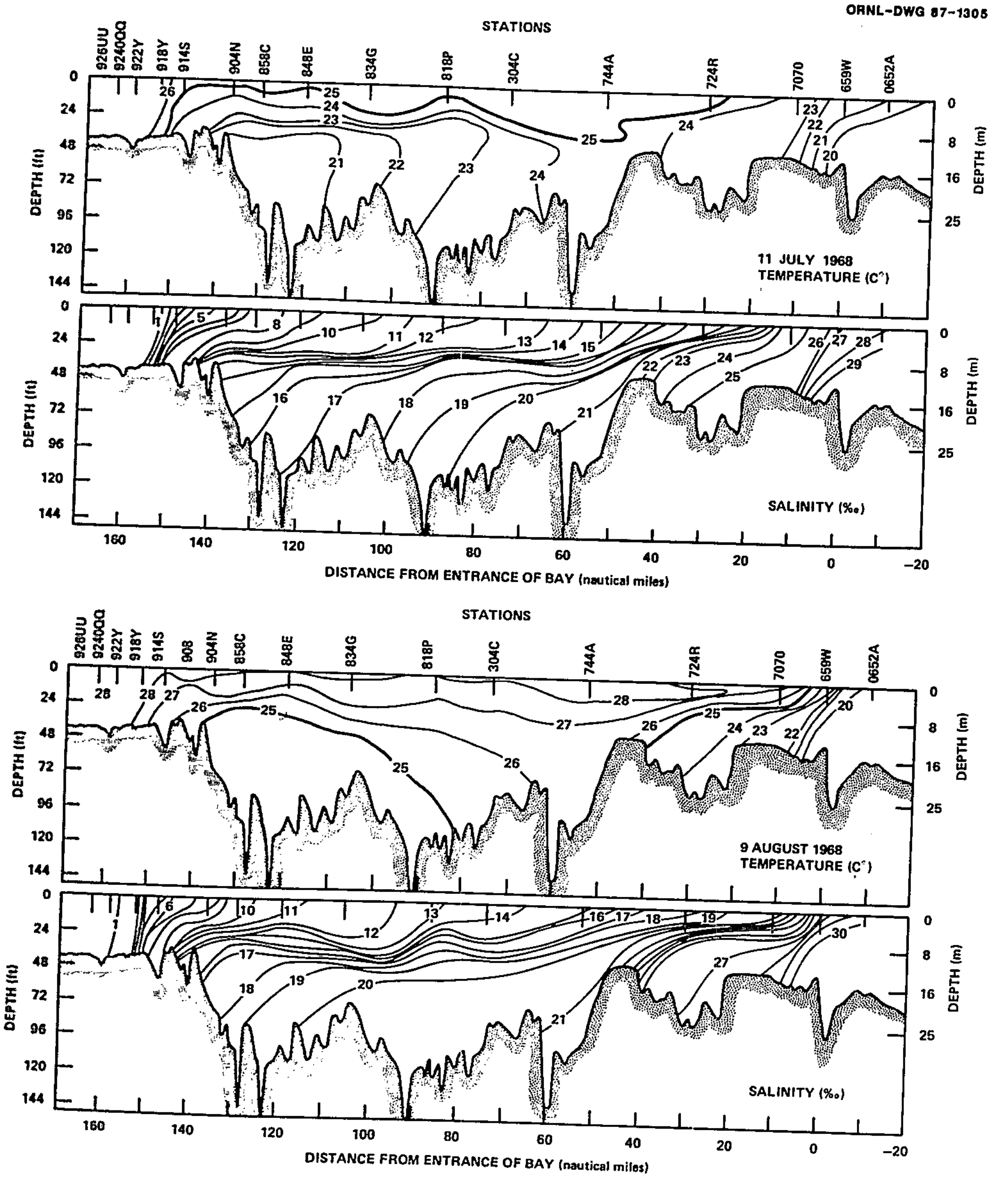

Fig. 5. (continued).

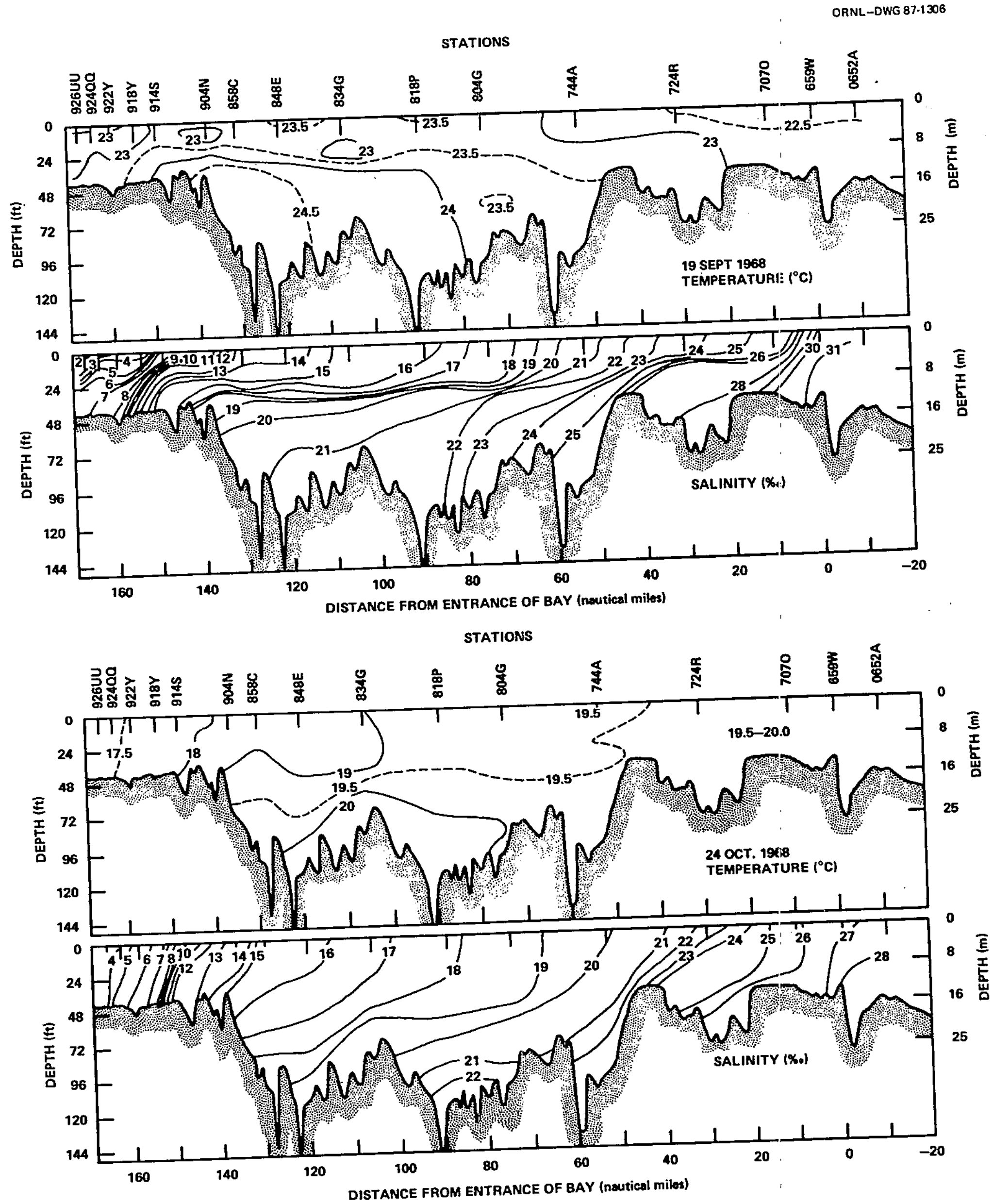

Fig. 5. (continued).

The most prominent feature for this discussion is a zone of residual cool water in summer centered 120-130 nautical miles (222-241 km) from the entrance to the bay, roughly between Annapolis and Rock Hall. This cool water is generally within the preferred temperature range of striped bass subadults and adults throughout the summer. The upstream boundary is sharply defined at an abrupt drop-off near Pooles Island, 140 nautical miles (259 km) from the mouth (about latitude 39° 20'). Upstream of this point the upper bay temperatures resemble other tributaries by exceeding preferred temperatures throughout the summer. Bathymetric charts show this most upstream end to be a narrow channel; the larger volume of water terminates midway between Rock Hall and the bay bridge (Fig. 6). There is no definite downstream boundary, for isotherms grade smoothly southward for many nautical miles in a manner that is seasonally and annually variable. Midsummer temperatures that would be selected by large striped bass have persisted downstream past Tilghman in some years (Stroup and Lynn 1963).

Of nearly equal importance for probable striped bass movements and seasonal distribution is a convergence of warm surface strata and a bottom sill near nautical mile 45 (latitude 37° 42'; 84 km from mouth), off the mouth of the Rappahannock River (Figs. 5 and 6). Surface warming in many summers would appear to provide an effective closure of the upper bay at this location for the seaward migration of large striped bass, which we would expect to avoid temperatures in excess of about 25°C. Although there are similarly shallow sills farther down the bay, they occur in waters cooler than 25°C. Upstream of the northernmost sill, large striped bass would be expected to follow declining temperatures in an upstream (northward) direction as summer warming progresses; downstream of this sill, the fish would be directed toward the bay mouth and the open coast where cooler waters prevail.

A thermal barrier at this location during many summers could help explain several facets of the ecology of striped bass in Chesapeake Bay. For example, the prominent southward migration observed in the bay in autumn by tag and recovery studies may reflect a movement by upper bay fish to repopulate the vacated (warm) sill and lower central basin area. Stock separation at the sill between the Potomac and Rappahannock Rivers could account for differences between the population dynamics of striped bass from the Virginia tributaries (especially the York and James) and those of the Potomac and upper bay stocks noted throughout the striped bass literature for the bay. These speculations require additional study for confirmation, but they indicate that thermal conditions possibly have major importance in the sill area.

The records show considerable interannual variability in the "coolness" of the residual pocket of cool water, the warmth of the overlying strata, and the strength of the convergence of temperatures above 25°C with the sill (in terms of how high the temperatures and the longitudinal distance covered). These differences are due partly to sampling at slightly different times of the year, but are most likely true interannual differences due to variable interactions of, for example, winter-spring freshwater flows, solar heating, air temperatures, ocean temperatures, and wind-driven circulation. Seliger et al. (1985) described some of these key climatic features that vary annually. The importance of variations in discharge of the Susquehanna River for stratification in the bay was emphasized by Schubel and Pritchard (1986). The thermal pattern of 1968 (Fig. 5) is not anomalous, for the pattern shows clearly in Fig. 7, which illustrates the average summer condition from 1949-61 (Stroup and Lynn 1963).

The interannual variability, however, encompasses widely different conditions with respect to probable striped bass movements in response to temperature. For example, bay water was sufficiently warm in 1968 to induce a thermal block at the sill (temperature >25°C) with a longitudinal extent of over 40 nautical miles (74 km), and to leave the cool pocket with temperatures only one degree below 25°C (Fig. 5). Large striped bass would have been severely blocked from moving out of the middle bay had they not already departed and would have occupied temperatures warmer than most would have normally frequented. In 1961, surface waters in the lower bay were exceptionally warm and the sill blockage even more extensive than in 1968, but the entire zone from the Potomac River mouth to Pooles Island was

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A

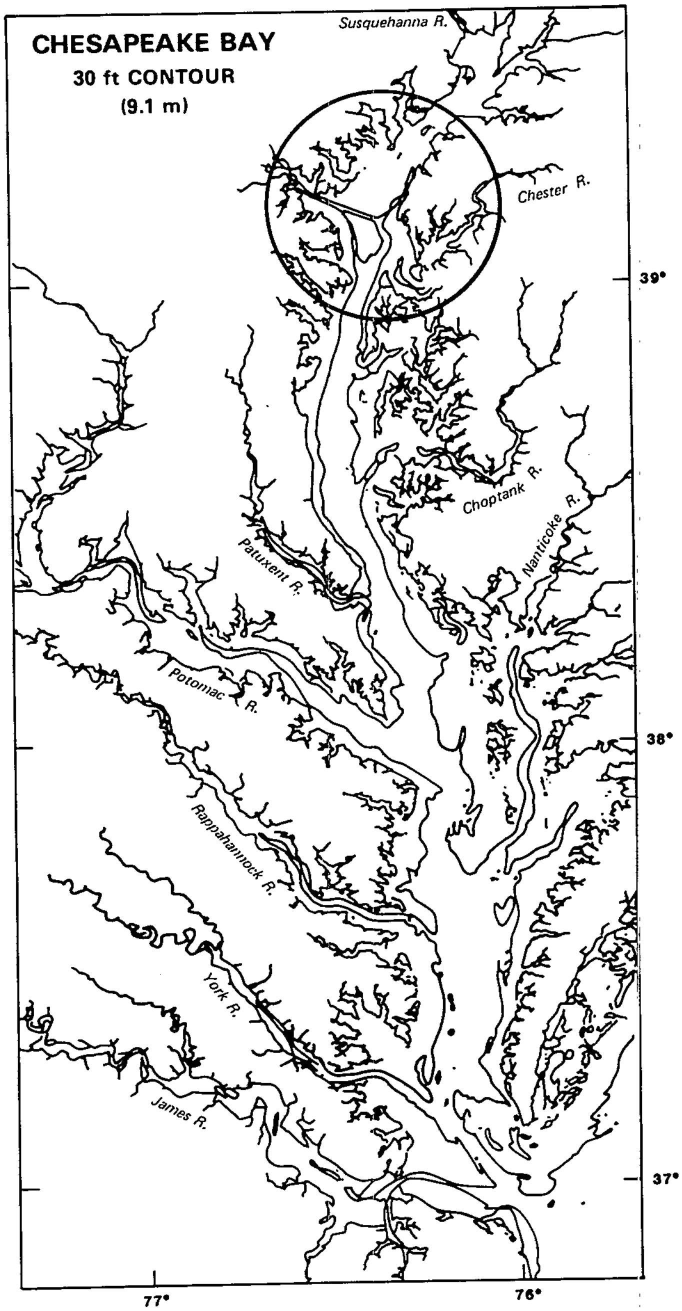

Fig. 6. Selected depth contours (A, 30 ft or 9.1 m; B, 40 ft or 12.2 m) for the Chesapeake Bay showing the horizontal extent of deep water in the Pooles Island-Rock Hall-bay bridge vicinity (upper circles on A and B) and the relatively shallow sill that cuts off the deep bay channel near the mouth of the Rappahannock River where maximum water temperatures occur (lower circle on B) (after Hires et al. 1963).

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B

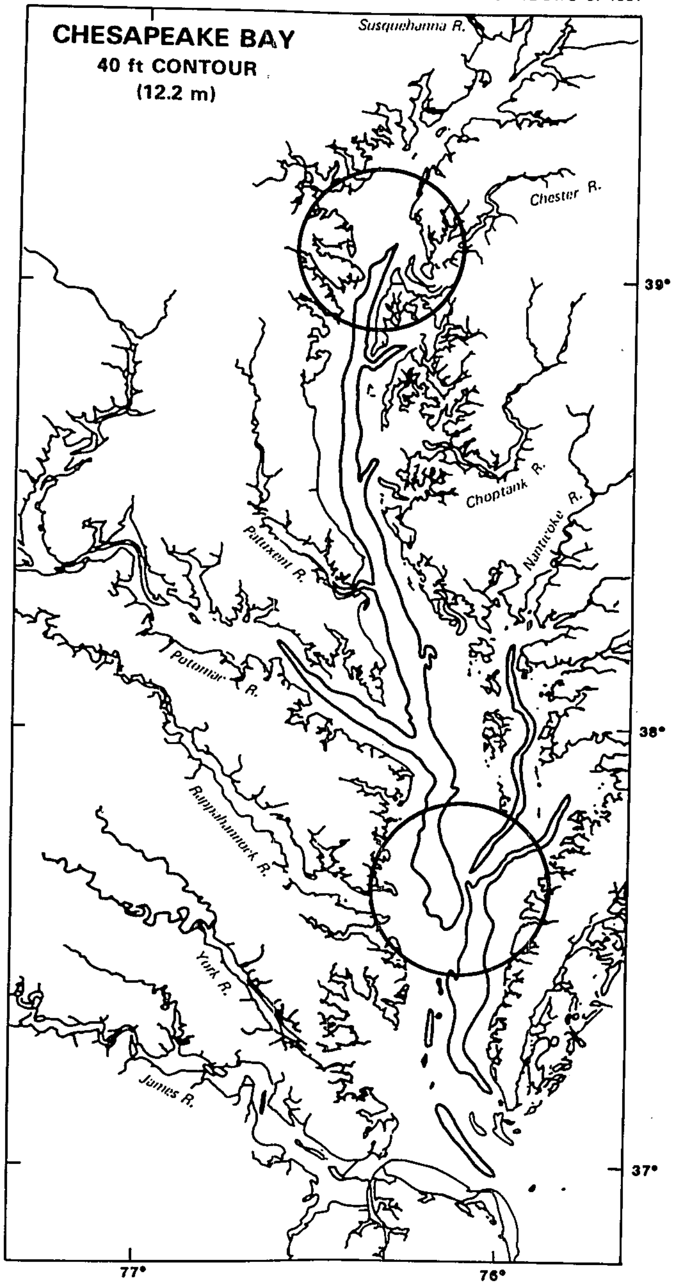

Fig. 6. (continued).

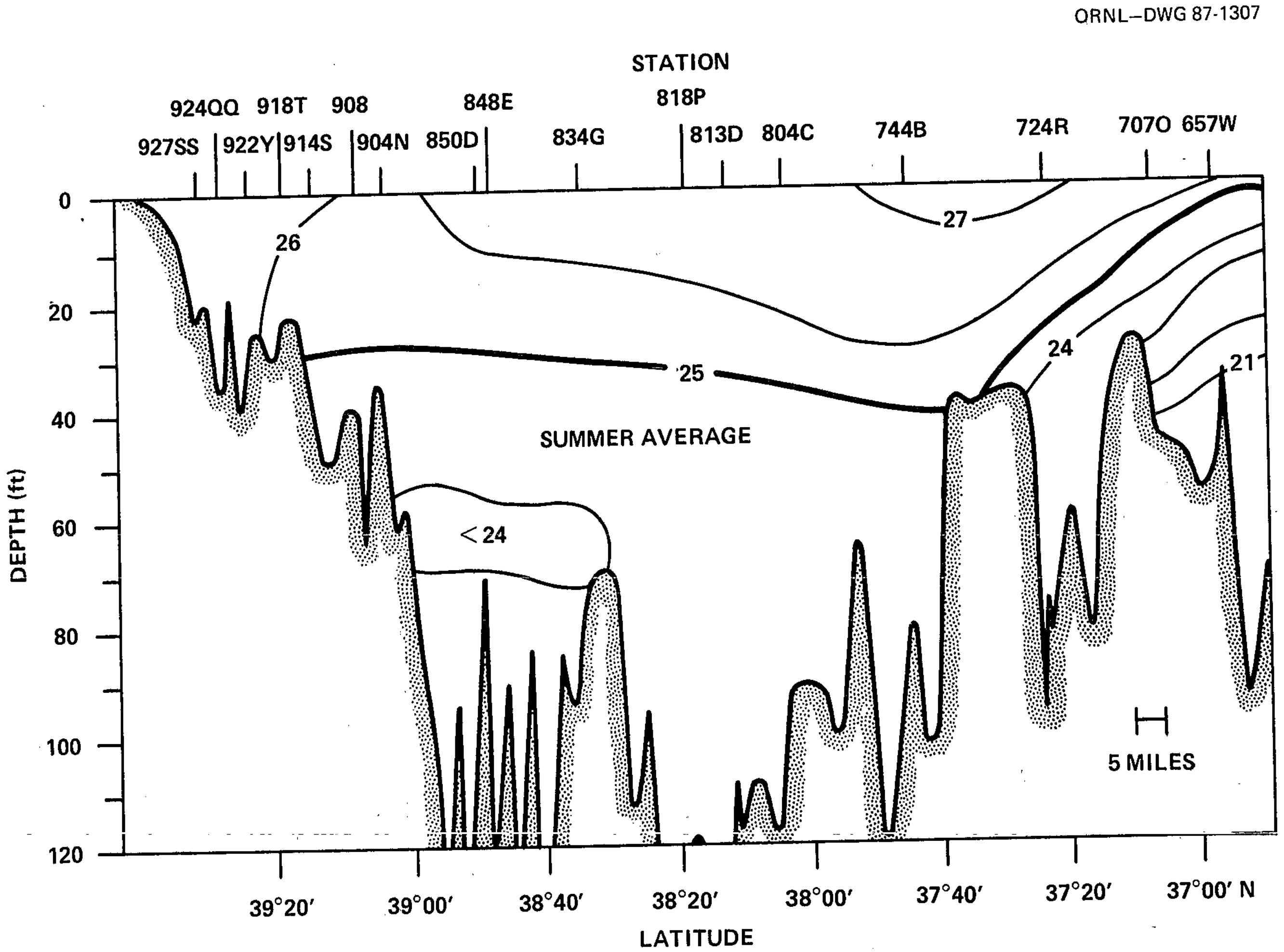

Fig. 7. Average summer temperatures along the longitudinal axis of the Chesapeake Bay, 1949-61 (after Stroup and Lynn 1963).

filled with water of 21-24°C (Fig. 8B) (Stroup and Lynn 1963). In 1958 (Fig. 8A), the 25°C isotherm does not appear to have reached the bottom at the sill, thus maintaining a migration access.

Interannual variability in temperature patterns, therefore, encompasses conditions that could either stimulate or prevent migration out of the bay to coastal waters and conditions that could cause severe or little crowding in the residual cool water (based on temperature alone). It appears that strong density stratification, as seen in 1961 (Fig. 8B), produces both especially high temperatures at the sill (and thus strong blockage) and preserves cool temperatures in the refuge. Historically, the two thermal effects may have compensated for each other somewhat in maintaining suitable striped bass habitat. Year-to-year differences in temperature distributions and thus striped bass distributions may have functional significance for widely varying year-class success of this species.

There is only sketchy evidence to suggest a change in thermal patterns in the bay that correlates with drastic population declines of striped bass since the early 1970s. The EPA Chesapeake Bay Program data set suggests that surface waters in the uppermost reaches of the bay may have been more consistently above 25°C since 1969. Thermal power stations such as the Calvert Cliffs station or those on the Potomac River might be adding sufficient heat to affect large areas of the bay in marginal years (although we have not examined their influence rigorously). Priority zones to consider when examining long-term temperature records to establish if there has been a general temperature change important to striped bass would be the cool refuge below 15 m in the bay bridge-Pooles Island reach and the bottom water over the sill just north of the mouth of the Rappahannock River. The sill area near nautical mile 45 would appear to be an especially sensitive area for future anthropogenic heating, such as from thermal electric power plants.

Dissolved Oxygen in Chesapeake Bay

As suitable as the deep, cool water zone near the bay bridge seems for summer habitat of subadult and adult striped bass blocked upstream of the sill, its suitability is compromised by depleted concentrations of dissolved oxygen. Telemetry studies in reservoirs have shown that water masses at acceptable temperatures but with dissolved oxygen values less than about 2 mg/L will be actively avoided (Coutant 1985). This response, coupled with temperature selection, produces a summer habitat "squeeze" in which surface warming and deep-water deoxygenation by microbial respiration shrink the volume of suitable habitat, often to relatively tiny "thermal refuges." One can assume from the evidence gathered in freshwater reservoirs that striped bass occupying the central basin of the Chesapeake and, in particular, the cool water mass near the bay bridge in summer will be subjected to such a habitat "squeeze." Avoidance of unsuitably warm water at the surface (or horizontally, both laterally and along the longitudinal axis of the bay) and unsuitably low dissolved oxygen concentrations in the deeper water shrinks the habitable water volume.

Oxygen depletion is a major feature resulting from water pollution that regulatory agencies seek to control. Microbial activity, largely in the sediment, reduces dissolved oxygen in the overlying water mass by decomposing (oxidizing) organic wastes and the accumulated remains of phytoplankton. Phytoplankton in the water is stimulated to grow in large numbers by discharge and runoff of nutrients. Although water temperatures may not have changed markedly in recent decades, the degree of deep-water deoxygenation certainly has, both in lakes and reservoirs undergoing eutrophication and in estuaries (e.g., Officer et al. 1984; Price et al. 1985). The central basin of the Chesapeake Bay experiences some summer oxygen reduction naturally (Newcombe and Horne 1938; Taft et al. 1980). However, trends that suggest increasingly depleted oxygen resources, mostly in summer, have aroused considerable concern among scientists and water quality regulators alike (Heinle et al. 1982; EPA 1983; Officer et al. 1984; Price et al. 1985; Seliger et al. 1985).

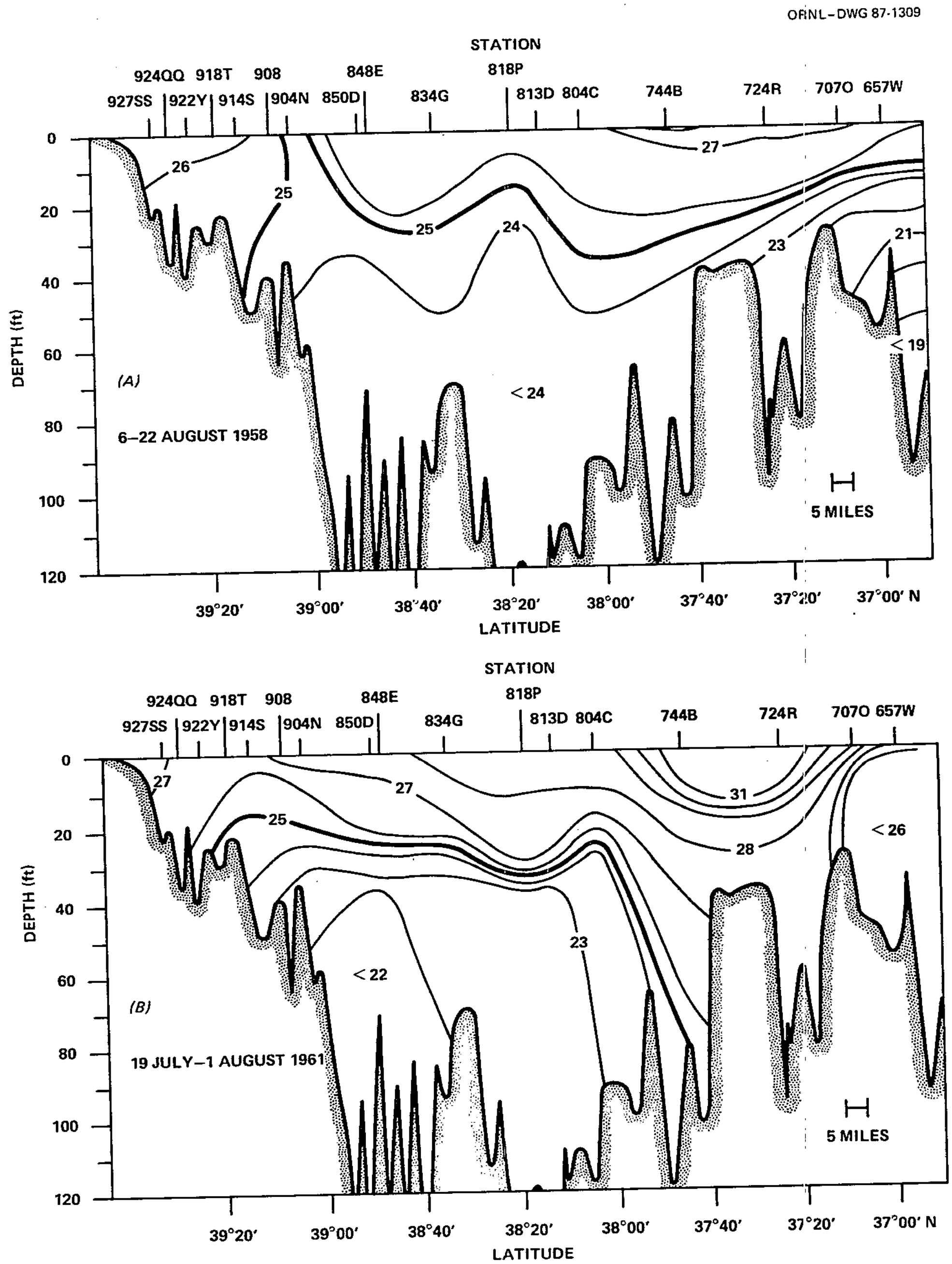

Fig. 8. Contrasting summer water temperature conditions along the longitudinal axis of the Chesapeake Bay (after Stroup and Lynn 1963). In a cool year (A) the 25°C isotherm does not reach the sill at nautical mile 45; in a warm year (B) temperatures there exceed 27°C. Strong density stratification seems to produce both especially high temperatures at the sill and cool temperatures in the residual pocket.

It is clear from the analyses by Officer et al. (1984) and Seliger et al. (1985) that two of the areas where dissolved oxygen in summer has been degraded most severely between 1950 and the present lie (1) in the "thermal refuge" near Baltimore and the bay bridge and (2) in the reach near the mouth of the Potomac River upstream of the sill (Fig. 9). Historically, the reach just upstream of the bay bridge seems to have maintained high dissolved oxygen values in spite of oxygen depletion elsewhere, although the data are sparse (Hires et al. 1963) (Fig. 10). Heinle et al. (1982) included the refuge area in the zone called "heavily enriched" with nutrients, and the sill area in the zone where oxygen has shown marked change. Much of the deep-water zone between these two areas has also shown expansion of both the bottom area and the water column thickness affected by low dissolved oxygen.

Shrinking Habitat for Striped Bass Due to Temperature-Oxygen Squeeze

Progressive restriction of habitat for subadult and adult striped bass in Chesapeake Bay by the combined effects of high temperature and low dissolved oxygen can be seen over the decade and a half (1965-80) for which most data were filed on the EPA Chesapeake Bay Program computerized data set when we conducted these analyses. For our analysis we illustrated the suitability of habitat during July on schematic water columns for the standard EPA bay zones (these drawings are too numerous to be reproduced here). The cool thermal refuge is generally represented by data from zone CB-3, in which most data were taken from the deep channel area. Zone CB-4 generally represents the upper part of the central basin, and CB-5 the lower part terminating about at the sill.

Although the data are sparse and discontinuous, the pattern for zone CB-3 shows suitable habitat through a large segment of the water column. Habitat limitation is mostly by high temperature at the surface. In zone CB-4, however, a pronounced squeeze is noticeable in most years, intensifying with time over the years examined. In CB-5, there are so few data from deep water that a pattern cannot be shown.

A dynamic picture of the generally concurrent seasonal warming and deoxygenation processes as they appear to us to generate a habitat squeeze for large striped bass has been outlined for the Chesapeake Bay by Schubel and Pritchard (1986). The exact pattern will vary from year to year as numerous climatic and other environmental factors (mentioned in the temperature section) vary.

The onset of deoxygenation in the lower layers of the bay is ascribed by Schubel and Pritchard (1986) to (1) a sharp increase in stratification following the spring freshet, (2) a change in the thermal structure from near vertical homogeneity to a condition of warmer surface and cooler depths, which adds to the density differences due to vertical differences in salinity, and (3) a decrease in the intensity and frequency of high winds that accompanies the transition from spring to summer.

Timing and duration of high Susquehanna River flow in spring have major impacts on initiation of oxygen conditions. Early freshets (winter) are dissipated in the bay by strong winds, and oxygen depletion is delayed until thermal input causes stratification in summer. Late freshets (April and May) cause strong salinity stratification which, augmented by rising surface temperatures, isolates bottom waters and speeds the onset of low dissolved oxygen conditions. Intensity of the low-oxygen condition (i.e., longitudinal extent and vertical thickness of layers with low dissolved oxygen) depends to a considerable extent on the accumulated freshwater discharge in May through July.

The duration of hypoxia in the upper bay is also affected by the Susquehanna River discharge. The end of the hypoxic period is associated with a weakening of vertical stratification and a downward mixing of higher-oxygen surface waters in the face of autumn winds and cooling temperatures, a process that normally occurs in September but can occur in late August or early October. Citing Goodrich (1985), Schubel and Pritchard described how the influx of fresh water in this period can strengthen vertical stratification in opposition to the forces that would otherwise weaken it. Overturn of the water column is delayed and hypoxic conditions persist until some time in October.

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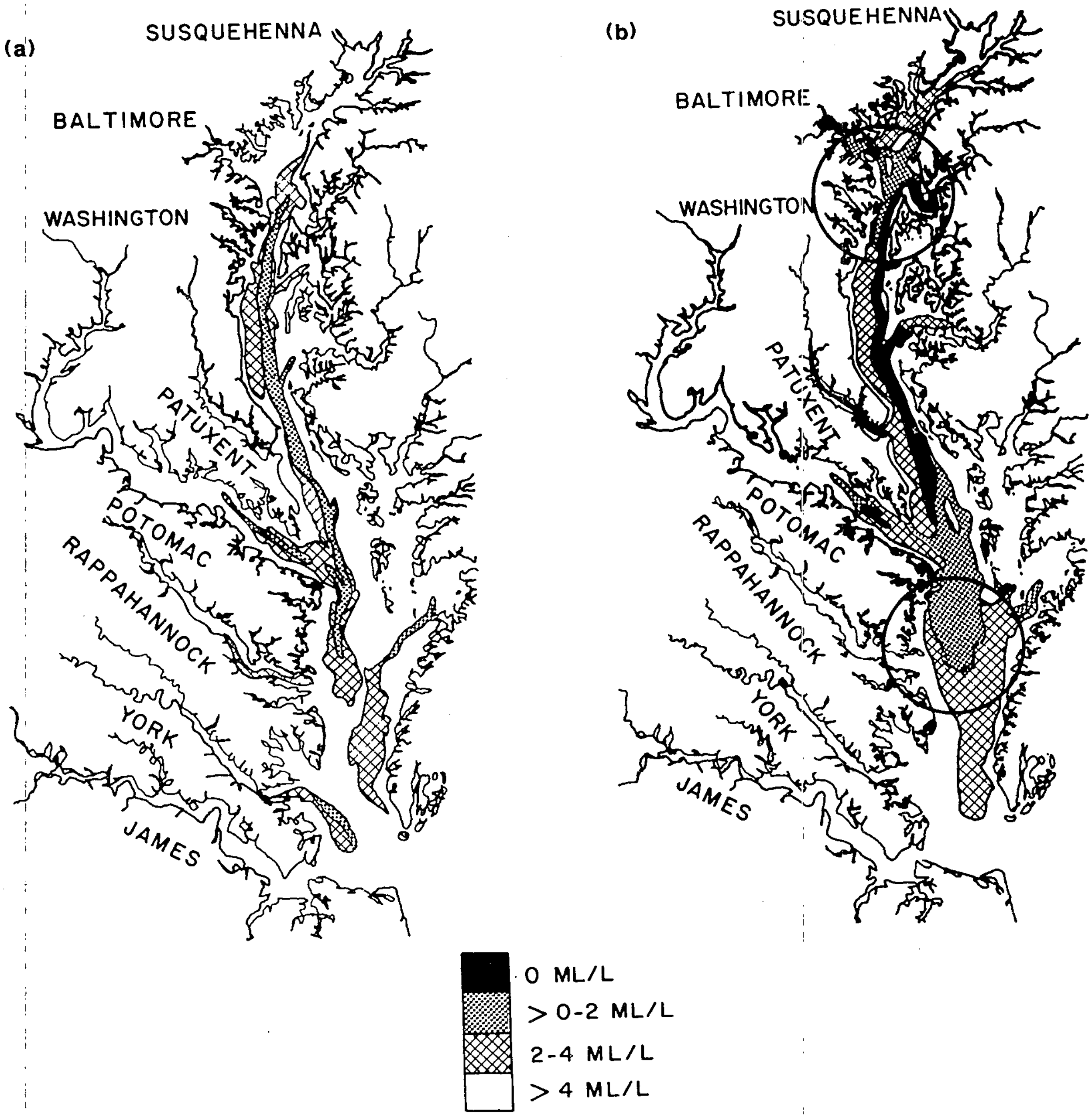

Fig. 9. Area of Chesapeake Bay bottom affected by low dissolved oxygen levels in the summers of 1950 (A) and 1980 (B) (after Officer et al. 1984). Two areas showing marked decrease in summer oxygen resources are off Baltimore (upper circle on B) and between the Rappahannock and Potomac rivers (lower circle on B) that correspond to the bay bridge thermal refuge and upstream of the sill, respectively.

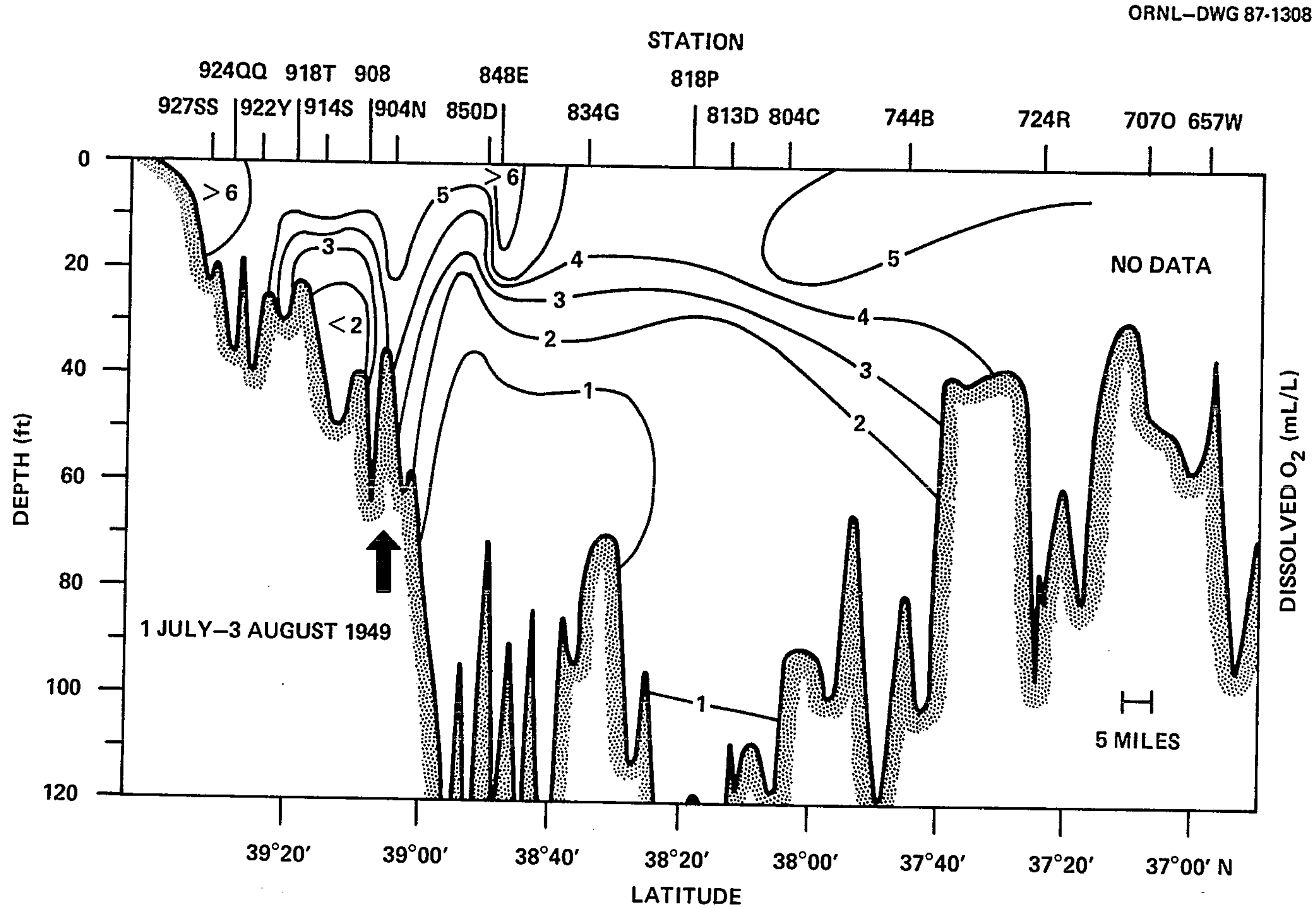

Fig. 10. Dissolved oxygen concentrations with depth along the longitudinal axis of the Chesapeake Bay in summer 1949 showing a zone of high oxygen content extending to the bottom in the vicinity of the bay bridge (arrow).

We have translated these processes into influences on striped bass adults and subadults (Fig. 11). In spring, high freshwater flows from the Susquehanna River establish a strong density stratification. The greater the freshwater flow, the more intense is the stratification. Striped bass overwinter in the deep basin oxygenated by vertical mixing in fall and winter and by a density underflow from the coast. Especially cold, windy winters will probably have the coolest and most well oxygenated deep water.

Vertical stratification is intensified in spring by warm riverine flows (that attract spawning striped bass) and solar heating of the bay surface. Oxygen depletion begins in the deep basins. By late spring or early summer, riverine inflows including tributaries exceed 25°C and are avoided by large striped bass while the bay surface is near 25°C. The warmest surface waters lie above the lower main basin. Low dissolved oxygen values occur in progressively shallower depths, and the density return flow is largely anoxic from decomposition in the downstream end of the central basin. Striped bass subadults and adults begin to be squeezed vertically, and some escape the main basin over the sill. Others move northward toward the residual cool water.

By a typical midsummer, warm (>25°C) water at the surface has impinged on the bottom at the sill, closing the upper and middle bay to emigration. Low dissolved oxygen has overlapped warm surface water in all but the uppermost reach of the basin, excluding large striped bass. Subadults and adults trapped upstream of the sill crowd in the refuge near the bay bridge, while those downstream of the sill can still follow the thermal gradient toward cooler coastal waters. Declining temperatures and wind-induced destratification in autumn replenish striped bass habitat in the main basin and tributaries, and the fish respond by spreading out, particularly southward. As the bay becomes colder than the coast, some fish continue past the sill, toward the warmer ocean temperatures that are now closer to preferred.

In this hypothesized sequence of habitat changes, two areas are critical zones for striped bass survival: the thermal refuge near the bay bridge and the sill. These areas most warrant special attention in monitoring and remedial action.

Models of the deoxygenation process (Taft et al. 1980; Officer et al. 1984; Seliger et al. 1985) could be combined with temperature and circulation models (e.g., Elliot 1976; Goodrich 1985) to more quantitatively estimate the timing and extent of habitat exclusion. Such models have been developed for freshwater reservoirs (Brown 1983; Brown et al. 1985). The models could illustrate the annual variability in habitat suitability and in fish movements and concentrations caused by variable climatic factors. In addition to the generalized features averaged over several weeks, one should also consider the effects of the prominent tilting of density clines by winds, and thus shifting of temperature and oxygen regimes (Carter et al. 1978). The models could also include the weather-related mechanisms of induction and destruction of density stratification that affect striped bass habitat (Goodrich 1985).

Physiological Effects

The long-term trend of progressively greater deoxygenation in the cool refuge must increasingly require subadult and adult striped bass to occupy waters with warmer temperatures and/or lower concentrations of dissolved oxygen than normal, with resulting physiological stress. Physiological stress of this type in freshwater reservoirs has led to reduced reproductive capability (Coutant 1987). This reduced capability took two main forms: (1) reduced percentage of adult females capable of spawning and (2) reduced survivorship of eggs and larvae after successful spawning. These effects were demonstrated by 6 years of controlled hatchery spawning of stocks derived from reservoirs with differing water quality. Reduced survivorship in the early life stages has been characteristic of reproduction in the Chesapeake Bay in recent years.

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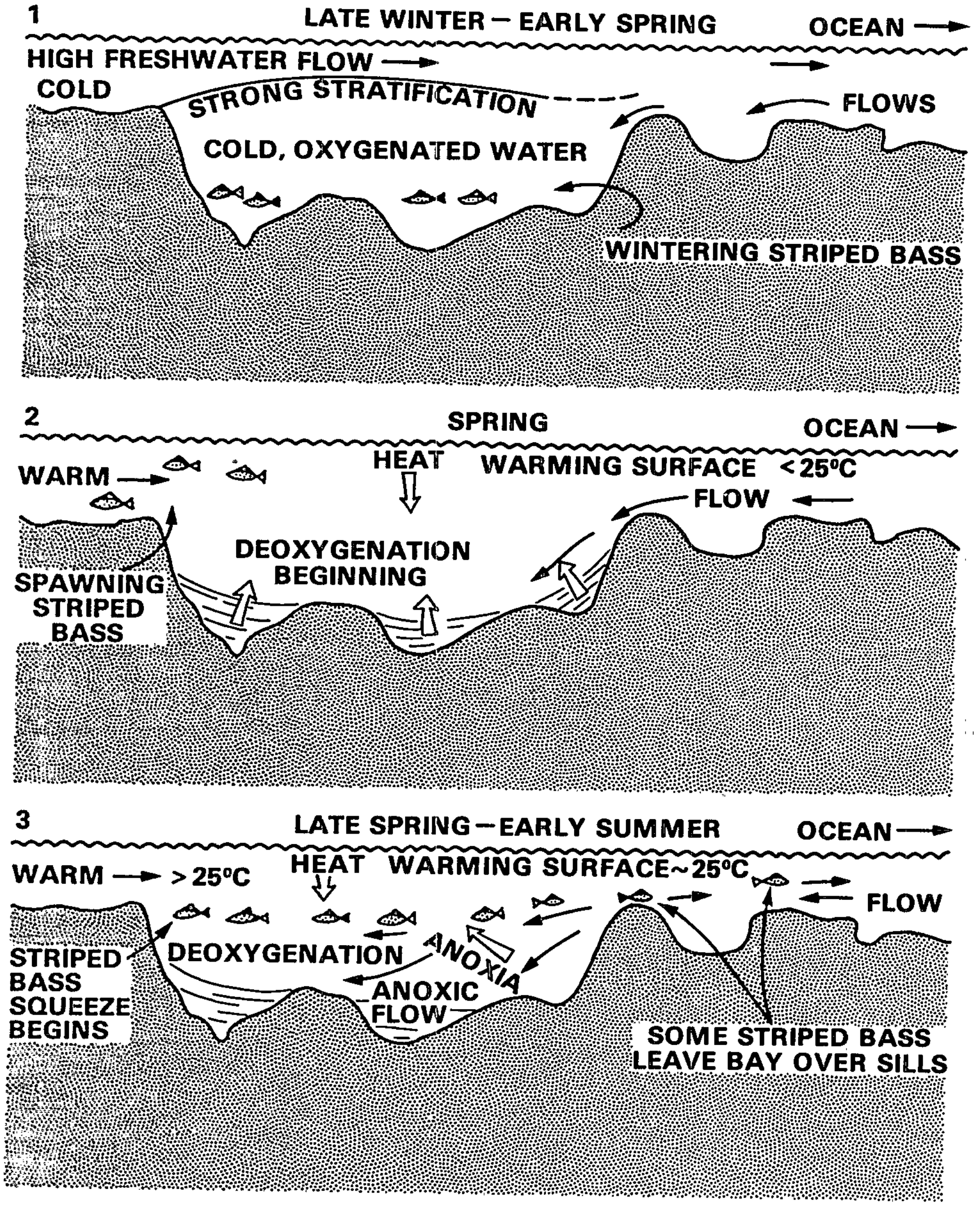

Fig. 11. Hypothesized chronology of typical seasonal changes in distributions of temperature, oxygen, and subadult and adult striped bass along a longitudinal axis of the Chesapeake Bay, illustrating the seasonal habitat squeeze imposed by surface warming, oxygen depletion from below, and thermal blockage at the sill. Two critical habitat zones are identified in summary.

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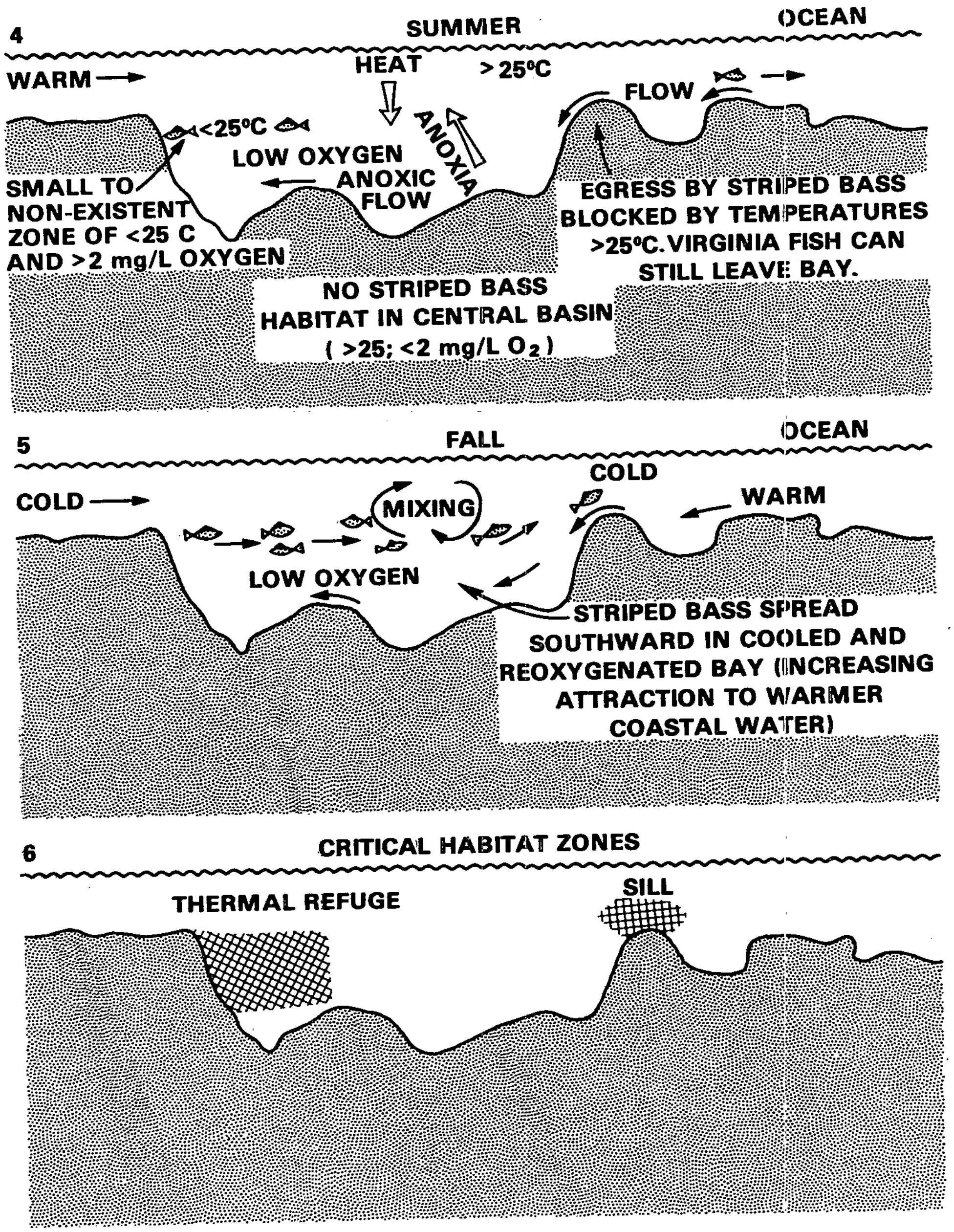

Fig. 11. (continued).

On the basis of our experience in freshwater reservoirs, including the hatchery study of reproductive success of stressed fish, and the trends we have seen in Chesapeake Bay, we propose a cycle of reproductive impairment for striped bass that may be a contributor to population decline (Fig. 12). This cycle would project the effects of temperature and dissolved oxygen that are manifested in individual fish (distribution, physiological stress) to possible impacts at the population level.

Could physiological stress from limited summer habitat induce declines of Chesapeake Bay striped bass? We attempted to correlate summer habitat size with the 1954-86 record of the Maryland Striped Bass Juvenile Index (obtained from H. Speir, Maryland Department of Natural Resources). Regrettably, the water quality data are not complete enough to estimate habitat size accurately for adults during the summers preceding most spawning years. However, two selected years seem to indicate linkage. The years 1980 and 1984 exhibited especially severe anoxia (Officer et al. 1984; Seliger et al. 1985, respectively). Each of these years was followed by a record low juvenile index for the upper bay (0.3 each year compared with a 1979-86 average of 3.3, or 4.3 excluding the two record low years).

There is also physiological evidence of stress severe enough to cause mortality of adult males between the springs of 1984 and 1986. Chapman (1987) surveyed mitochondrial DNA genotypes in males from the relatively strong 1982 year class in the springs of 1984 and 1986 and found dramatic and significant change in this biological marker. Discounting the possibly real errors of sampling and of different genotypes having different ages of maturation, the hypotheses Chapman advanced for the change in genotypes are heavy mortality of the stock sampled in 1984 and immigration of a different stock (speculated to be from the York, James, or Hudson rivers) to the upper bay prior to the 1986 spawning season. As the summer fishery is relatively small, and Maryland banned all fishing for striped bass as of January 1985, fishing mortality may be a minor source of the depletion. This information is consistent with environmentally induced stress and mortality of mature upper bay males over the strongly hypoxic summer of 1984 and a partial replacement of them by stocks from the lower bay that had summertime access to coastal waters beyond the sill.

Other Species

The striped bass is not the only species experiencing reduced numbers in the Chesapeake Bay. Populations of other species such as the American shad (Alosa sapidissima) and the blueback herring (Alosa aestivalis) have also declined over the same time period, generally since the early 1970s (Richkus and DiNardo 1984). Although temperature preference information for these species is less available, it seems reasonable to infer that the habitat restrictions discussed for striped bass would apply to any cool water species or cool water life stages. Adult alewife (Alosa pseudohasengus), one of the "river herrings" in the bay, displayed upper avoidance in the field at 22°C (Wells 1968) and showed preference in laboratory experiments for 21.3°C (Reutter and Hendendorf 1974). In addition, prey species would be at risk from concentrated predators in the minimal habitat space that several species must share. It follows, and should be confirmed, that the zones found to be important for striped bass are likely to be important for other species as well.

Remedial Action

It is certainly premature to recommend remedial action measures for Chesapeake Bay on the basis of this tentative analysis. Nonetheless, some preliminary thoughts may be fruitful for planning. Reducing warm temperatures in surface waters in summer, especially at the sill, may not be possible. Should further analysis show that thermal power stations such as Calvert Cliffs or those on the Potomac contribute substantially to the heat load of the sill area in summer, then reducing those heat loads would be advisable to preserve migration access. Dredging the sill to provide a deeper and cooler route of egress could be beneficial to striped bass in moderately warm years.

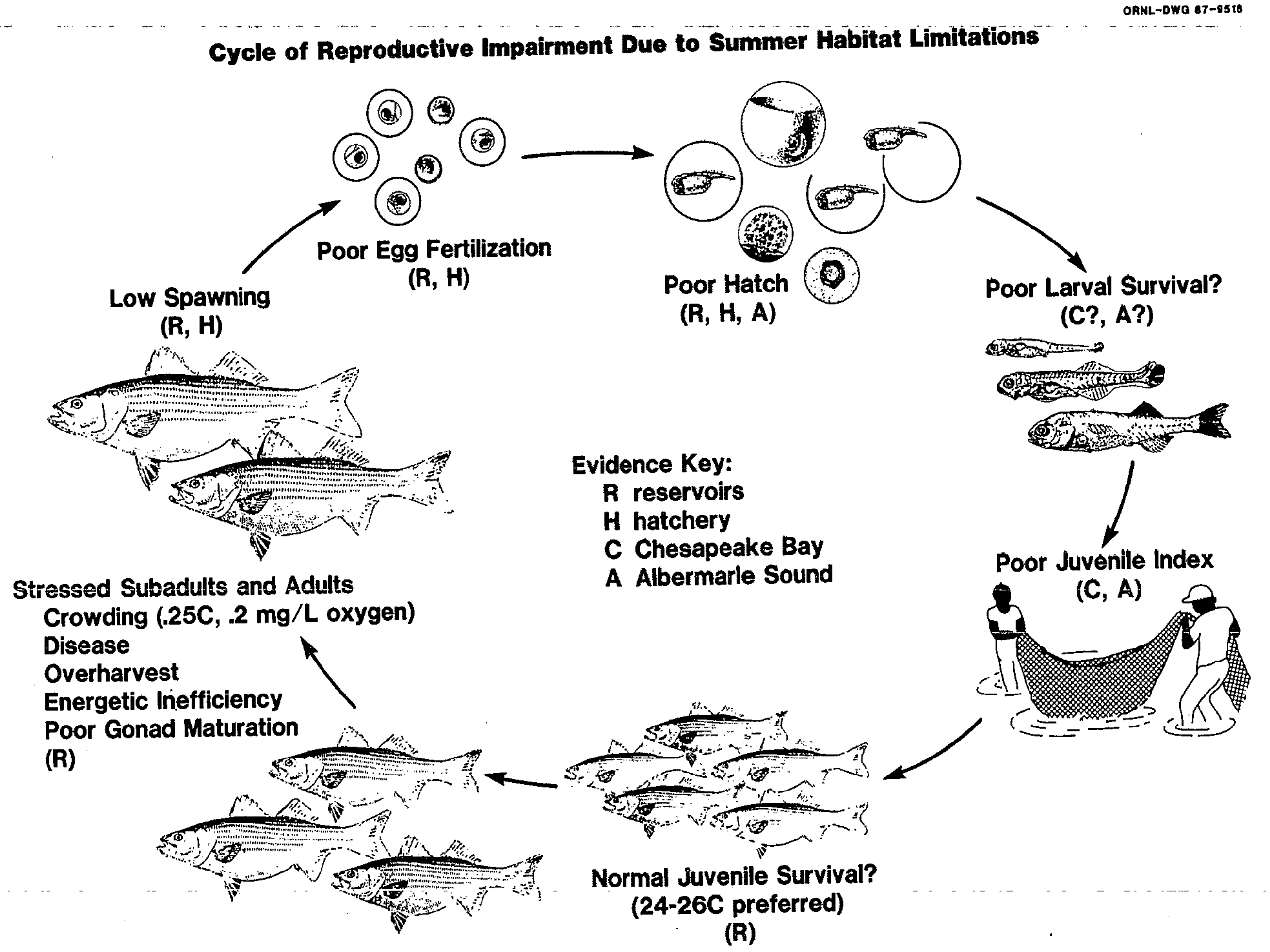

Fig. 12. Hypothesized cycle of reproductive impairment of striped bass due to summer temperature and dissolved oxygen habitat limitations.

The long-range solution to oxygen depletion seems to be reduction in nutrient input to the bay. This will probably be difficult because inflows are heavily from non-point sources in the watershed. Despite such efforts to reduce nutrient loading, however, the nutrient inventory in the bay is likely to be sufficient to sustain high plankton production and strong anoxia for many decades due to the countercurrent circulation of estuaries that tends to trap nutrient-rich sediment. Early results from the EPA-sponsored steady state model of the bay's nutrient cycling indicate that sediments contribute a significant proportion of nutrients to the water column (HydroQual, Inc., as reported in Chesapeake Citizen Report, Spring 1987). A short-range step for protecting the integrity of the thermal refuge near the bay bridge could be artificial deep-water reoxygenation, which has been successfully accomplished in lakes and reservoirs (Fast 1974; Fast et al. 1975).

III. Albemarle Sound

Striped Bass in Albemarle Sound-Roanoke River

Albemarle Sound is one of the principal estuaries of the east coast of North America (Fig. 13). With its companion estuary, Pamlico Sound, and adjoining waters, it forms a major brackish water body between the barrier islands of the Cape Hatteras area and rivers draining the lowlying northeastern coastal plain of North Carolina. Albemarle Sound and its tributaries have a surface area of approximately 253,783 ha. The major inflow is from the Roanoke River, although the Chowan River and numerous other tributaries have large expanses of open water in their lower reaches as a result of sea level rise into preformed river valleys. Albemarle Sound is not continuous with the Atlantic Ocean; outflowing water passes through narrow Croatan and Roanoke sounds before reaching Oregon Inlet and the ocean. Salinity ranges from a high of about 28 parts per thousand (ppt) in lower Croatan and Roanoke sounds to about 1-2 ppt at the surface near the mouths of the Alligator and Pasquotank rivers, with no salinities at the surface in the western sound. Brackish water, especially as a wedge at the bottom, intrudes into the central and western sound to degrees that vary with climatic conditions.

The striped bass is considered the premier fish species of the Albemarle Sound-Roanoke River area, yet its population has been in steady decline since the mid 1970s (Mullis and Guier 1981). Since 1970, no dominant year class of striped bass has been produced in Albemarle Sound, and no significant year classes have been established since 1976 (Hassler et al. 1981; Kornegay and Mullis 1984). This continuing lack of recruitment to the adult population has been reflected in declining catches of striped bass by sport fishermen (Mullis and Guier 1981) and commercial fishermen (Hassler et al. 1981).

The problem with the Albemarle Sound stock of striped bass is likely endemic, despite a general decline in striped bass populations along the Atlantic coast (Hodel and Baldrige 1985). The Albemarle Sound stock is principally a resident stock that does not participate to any large degree in the well-known coastal striped bass migrations. Merriman (1941), Vladykov and Wallace (1952), and Hassler et al. (1981) conducted tagging and recovery studies in which very few striped bass marked in the sound were recovered in coastal waters. The migratory coastal stocks are largely derived from the Chesapeake Bay.

Coincident with population decline has been a drastic drop in viability of eggs spawned in the Roanoke River, the main spawning tributary for striped bass in Albemarle Sound. The decline began in 1975, and egg viability has continued to be low ever since (Hassler et al. 1981; Kornegay and Mullis 1984). Viabilities of 79-96% characterized spawning from 1960 to 1974, but values have been only half that in recent years (although with considerable interannual variability). Although the number of eggs spawned did not fluctuate greatly through 1980, the reduced number of eggs capable of hatching has caused concern. The cause of loss of egg viability has been a mystery. In vitro experiments with striped bass eggs suggested that parental influence, perhaps toxic materials transferred to eggs, was important for suppressing egg development (Guier and Mullis 1982).

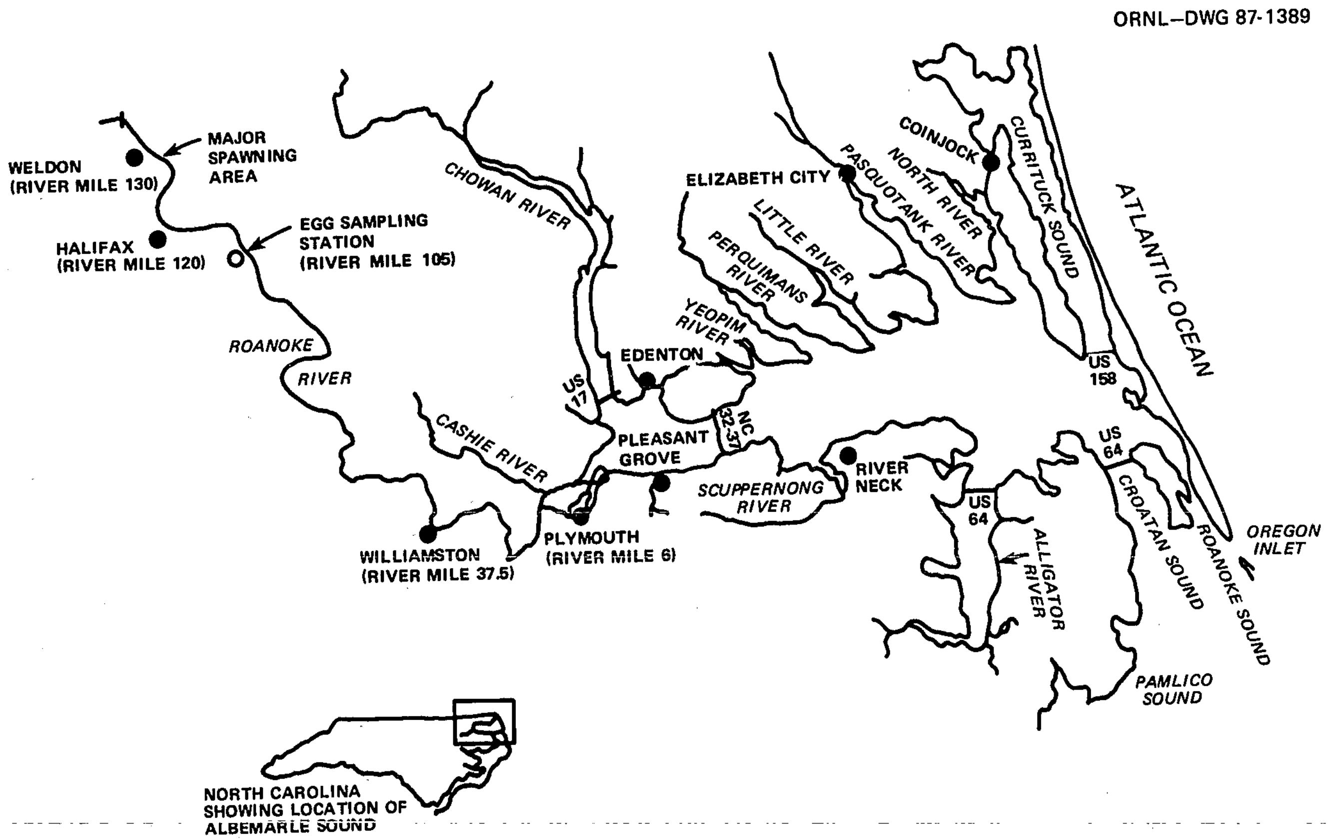

Fig. 13. Map of Albemarle Sound and its major tributaries.

Once hatched, larval striped bass have also exhibited abnormal development and survival. Rulifson (1984) found abnormally large numbers of surviving larvae with empty stomachs at a time when they should be actively feeding. Whether this condition is due to lack of suitable food resources or inability of larvae to feed appropriately is not known.

Three anthropogenic influences have been implicated in the plight of the Albemarle Sound striped bass (Kornegay 1985). Roanoke River dams, built for flood control and electricity generation, have altered natural flow patterns and temperatures of the river. These altered flows and temperatures may delay spawning, disconnect the timing of larval production and food development, and flush larvae to unproductive zones. Overharvest of the spawning stock, principally by heavy fishing in the sound, may have generally reduced the number of spawners. Increased pollution, especially of the western sound, where blue-green algal blooms and increased deoxygenation have been evident since the mid 1970s, may contribute to direct mortality or to transfer of toxicants.

Each of these mechanisms as currently conceived does not, however, adequately explain many features of the stock decline. These features include persistence of typical numbers of adult spawners well after the juvenile numbers began to decline markedly, nonviable eggs at the spawning grounds despite presence of typical numbers of eggs being spawned, and high larval mortalities in zones upriver of major pollution in the western sound (algal blooms and anoxia).

A New Hypothesis for Striped Bass Decline in the Albemarle-Roanoke System

The recent synthesis of ecological data on striped bass in both fresh and saltwater environments (Coutant 1985) and the foregoing analysis of Chesapeake Bay suggest that distribution and population declines of this species in Albemarle Sound might also be related to habitat selection according to thermal preferences alone or in concert with dissolved oxygen. The species may have only limited zones of the sound available to it during critical times of the year, such as summer. We thus initiated an evaluation of the Albemarle Sound as a second case study for prioritizing zones for pollution monitoring and control in estuaries.

Cursory evaluation of available information on the Albemarle-Roanoke system suggests a scenario consistent with a temperature-oxygen squeeze for subadult and adult striped bass in the sound. Zones that could be especially important for monitoring and control of water quality have been tentatively identified. Avoidance of high temperatures and low oxygen levels in increasingly deoxygenated deep water of the sound seems to concentrate the larger fish. This concentration alone could lead to summer stress of reproductive stocks and consequent reduction in egg viability. The habitat squeeze may also concentrate fish in restricted zones containing particularly high concentrations of toxic materials, such as those derived from pulp mills near the mouth of the Roanoke River. Additional work is required to more fully flesh out the habitat selection scenario based on available data, and to conduct the necessary field studies to test the hypothesized mechanisms and to more closely identify the critical locations.

Much of the sound appears to be unsuitably warm for subadult and adult striped bass in summer, and is likely vacated then. The bulk of Albemarle Sound is shallow, vertically well mixed, and warm in summer. Midsummer temperatures measured in 1985 in transects across the eastern, central, and western parts of the sound exceeded 25°C, the upper avoidance temperature for larger striped bass, at all depths (Mullis, personal communication). Most temperatures (taken on August 27-29, 1985) were 26.5-27.5°C. The exception to the generalization of "well mixed" is a saltwater intrusion in the bottom meter or so, where temperatures remain high but dissolved oxygen levels drop markedly. Hypothesized avoidance of warm water (and perhaps low oxygen at the very bottom) in the eastern sound is supported by resource maps that indicate "rock" (i.e., striped bass) in the eastern sound in March-May and October-December, but notably not in June-September.

It is suspected that striped bass vacating the warm eastern end would follow thermal gradients to deeper and cooler zones (Fig. 14). The deepest parts of the sound are in the western half, roughly between Pleasant Grove and River Neck. Some may leave through Roanoke and Croatan sounds, although the tagging studies suggest not. Resource maps show striped bass historically occupying the deeper water off River Neck in July-October and the deeper mid-sound stretch between Pleasant Grove and the Highway 32 bridge year-round. Annual reports of tagging studies of primarily 2- to 4-lb striped bass by W. W. Hassler (summarized in Hassler et al. 1981; annual reports with detailed data submitted to the North Carolina Division of Marine Fisheries) show the general area of returns in June-September to be the mouth of the Roanoke River, the Edenton area, and eastward to about the Highway 32 bridge. The 1985 temperature-oxygen survey indicated the coolest temperatures in the western sound (although still above 25°C) to be at mid-depth just above a halocline, below which oxygen levels dropped.

The suspected historic refuge of relatively cooler water in the midwestern sound may be made increasingly less suitable by oxygen depletion. The western end of the sound is more eutrophic now than it was formerly (Mullis and Guier 1981; Mullis, personal communication). This trend is due to high nutrient levels in the Chowan River from agricultural runoff, pulp mill effluents, and leakages from a fertilizer plant near Tunis (that was closed). Blue-green algal blooms began appearing in the Chowan River in the early 1970s, concurrent with the first signs of poor striped bass reproduction. Elevated levels of organic matter could be expected to settle and decompose in the deeper reaches, where mixing is restricted by salinity stratification.

Evidence that stressful summer conditions are experienced by the larger striped bass in Albemarle Sound comes from evaluations of bony structures for aging these fish (Humphreys and Kornegay 1985). Scales, vertebrae, opercular bones, and (to a lesser extent) otoliths of fish collected in 1980 showed many false annuli, indicating periods of reduced growth in summer. Otoliths, in older fish in particular, exhibited an increased occurrence of false annuli.

Reduced reproductive competence may be the principal result of Albemarle striped bass being forced to reside through the summer in waters warmer than 25°C and low in dissolved oxygen. Crowding, direct mortalities, or deteriorating body condition have not been reported (although they may still occur). The reduction in egg viability recorded in detail for the Roanoke River striped bass spawners since the mid 1970s is very similar to the loss of egg viability observed for spawners from eutrophic Cherokee Reservoir, Tennessee (Coutant, 1987). This excellent set of data strongly reinforces the cycle of reproductive impairment we have proposed (Fig. 12).

Concentration of subadult and adult striped bass into restricted zones in summer due to temperature preference and avoidance of low oxygen levels may also expose them to particularly high concentrations of toxicants. It is reasonable to suspect that the cooler, deeper zones once occupied successfully by striped bass are also the zones into which toxic materials now accumulate (Coutant 1980). Deep-water reaches of the Roanoke River delta may be especially susceptible to both attracting striped bass in summer and receiving and retaining effluent materials from nearby pulp mills. The fish would be "forced" by temperature preferences to reside in just those zones which give them the maximum pollutant exposure. Even though not directly lethal, the toxic materials could manifest themselves in the developing eggs (as suggested by Guier and Mullis 1982).

The impact of a reduction in egg viability could be expected to be observed first in lower larval numbers in the Roanoke River and then in fewer young-of-the-year in the western sound, both of which were the first symptoms reported (Hassler et al. 1981; Hodel and Baldrige 1985). Continued production of normal quantities of eggs by a normal number of spawners (at least for the first several years after loss of egg viability) (Hassler et al. 1981) reflects survival of adults but under stressed conditions. Summer-stressed Cherokee Reservoir females produced normal egg numbers per female even though the population suffered heavy adult mortalities. Reduced production of young eventually reduces the adult

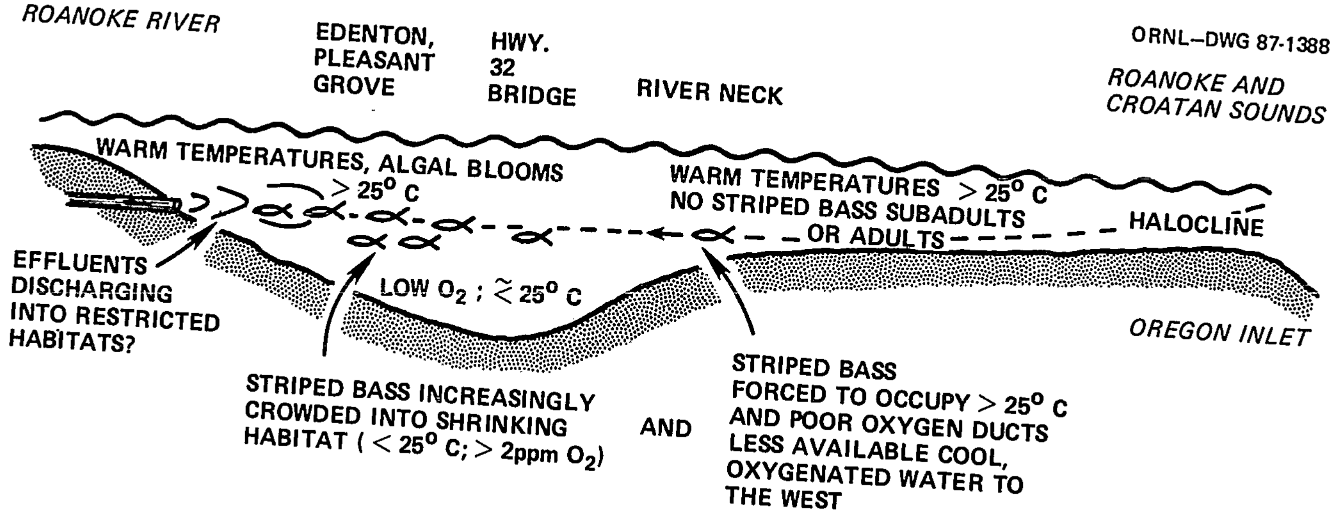

Fig. 14. Hypothesized summer striped bass distribution in Albemarle Sound, North Carolina, in relation to temperature and dissolved oxygen (vertical profile along the longitudinal axis; not to scale).

population. Mullis and Guier (1981) reported an increase in the average size of striped bass caught by Albemarle Sound sport fishermen from 1977 to 1980, attributed to fewer smaller fish being recruited to the population.

With increased population pressure from reduced habitat size for subadults and adults in the western "refuge," more fish could be expected to remain in the previously less suitable eastern zone. These fish are, in effect, squeezed by low oxygen to the marginal temperature conditions there. Those striped bass most able to tolerate this shift would be the younger subadults. There has, in fact, been a shift in distribution of the "nursery area" to the east in recent years (Hodel and Baldrige 1985). Mullis and Guier (1981) reported a shift in both fishing effort and harvest to more eastern portions of the Albemarle Sound area. Also, the catch has been dominated by younger fish (1+ and 2+ ages contributing an average of 69% of the annual sport harvest). The necessity for occupying water at temperatures above optimal for growth would explain the numerous false annuli reported by Humphreys and Kornegay (1985).

Because both temperatures and estuary mixing will vary from year to year (low mixing creating conditions for enhanced deoxygenation), there will undoubtedly be considerable interannual variability in habitat space available for subadult and adult striped bass. This variability will be reflected in the variable effects on egg viability in the Roanoke River the following springs. Egg viability has been shown to vary among years (Kornegay and Mullis 1984) although there has been no attempt to test statistical correlations with climatic conditions.

If the population problems with striped bass in Albemarle Sound are due to a temperature-oxygen squeeze aggravated by increasing deoxygenation and possible toxicants in the refuges, then it is unlikely that this would be the only species affected. Many estuarine and freshwater species have temperature preferences in the same range as those of subadult and adult striped bass. They could be expected to suffer from the same shrinking habitat. On the other hand, some other species prefer much warmer temperatures, and they would likely be less affected. In fact, all species harvested from Albemarle Sound except the warm-water largemouth bass and white catfish were declining in 1980 (Mullis and Guier 1981). Stocks of the anadromous alosid stocks of the Atlantic coast have been in decline over the same period as the general decline in striped bass stocks (Richkus and DiNardo 1984).

In summary, current information suggests that a critical zone of especially cool and oxygenated water is necessary in summer for maintaining a healthy population of striped bass in the Albemarle Sound system. That zone appears to be a reach of deeper water in the western sound, now still poorly defined. It is becoming increasingly eutrophic, and its suitability as the critical summer habitat for striped bass (as defined by thermal preferences) has been reduced because of progressively greater deoxygenation during the period of striped bass decline. The restricted zone of suitable habitat in summer may also be the site of heightened toxicant exposures.

CONCLUSIONS

What guidance has this study provided for the general problem of prioritizing pollution monitoring and control in estuaries? Our evaluation of habitat space for striped bass in Chesapeake Bay and Albemarle Sound as defined by temperature and dissolved oxygen concentration might be viewed as simply a parochial effort with the environmental biology of one fish species that happens to interest the authors.

First, the notion that critical zones in an estuary have a predominant influence on the "health" of the system seems supported, if not confirmed. These are not necessarily the places with greatest effluent discharge (as water quality engineers might suspect) or the places where organisms spawn (as biologists usually proffer).

The next lesson is that the zones will be recognized by interaction among spheres of investigation that are all too often separated. The health of an estuary is displayed in many ways, including declines in fishery productivity, changes in distribution patterns of important aquatic organisms, algal blooms, hypoxia and anoxia, numbers and kinds of pollutant discharges, and effluent toxicity. Specialization has led to creation of discrete disciplines that follow each of these topics with little reference to others. The relevance of other disciplines such as hydrography and sedimentary geology goes unexplored. The result is perpetuation of mystery rather than elucidation. Yet understanding the suitability of an estuary for continued population success of one representative fish species is shown here to depend on a blending of data gathered by all of the disciplines--water quality (temperature, oxygen), hydrography (seasonal water flow), sedimentary geology (coastal sediment import and sill development), fish physiology (temperature preferences), fisheries biology (seasonal behavior of the fish in the field), and so forth. It is not sufficient for pollution control agencies to concentrate on the traditional physical and chemical tools of the water quality trade.

Third, water quality measurements can be used to define the changing extent of suitable habitat in an estuary, not simply to show values on a tolerance scale. The volume of water having suitable qualities and its spatial and temporal distribution (and the reasons for changes in volume) constitute especially important information for resource management.

Fourth, many old data sets can be very useful for establishing patterns when there is a hypothesis against which to compare them. Elaborate computerized data management systems may not be the most useful for recognizing habitat trends, especially when their organization is not, or only poorly, consistent with natural estuary subdivisions.

Fifth, prioritization implies having a management objective. "Cleaning up the bay" is not a sufficiently clear objective to guide meaningful monitoring or control efforts when financial and human resources to accomplish it are necessarily limited. Priority areas can be defined when the analysis becomes specific enough to specify the requirements of the most valued components of the estuarine system, usually the living resources.

Sixth, the importance of temperature or, more correctly, the seasonal thermal structure of an estuary for controlling important biological responses is emphasized as a feature worthy of general attention. The seasonal distribution of organisms in relation to thermal structure appears to set the background against which maintenance of other habitat requirements (e.g., needs for dissolved oxygen, toxicity tolerance) should be judged.

Last, this analysis has tentatively identified critical zones in two major estuaries and offers promise that (1) the critical zones in Chesapeake Bay and Albemarle Sound may be further refined for benefit of all cool water species and (2) a similar evaluation in other estuaries using the temperature and oxygen requirements of indigenous species and broad knowledge of the estuary's geography and hydrography may be similarly productive.

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